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ORBITEC TELEROBOTIC CONTROL GLOVE

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FOR THE COMMANDER

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13. ABSTRACT *(Maximum 200 words)* This Final Report discusses the Phase I SBIR research results for a telerobotic dexterous end-effector control system. The ORBITEC Telerobotic Control Glove (OTCG) provides control of position and forces applied using the feedback of force and tactile information to the operator. This approach allows for a simple, low-cost, and light-weight controller that may be integrated and used with various dexterous end-effectors. The purpose of the Phase I effort was to establish feasibility of the OTCG approach. During the effort, various key master controller glove components were designed, built and tested by ORBITEC. Preliminary requirements and design for a prototype glove system were established. Proof of concept feasibility was accomplished through systematic testing of the key components. The results provide insight to a point design of the OTCG, which will allow telerobotic control of a variety of slave end-effectors with appropriate feedback mechanisms. This design may also be integrated with existing arm/wrist controllers. The Phase II effort will lead to development of a complete controller system which would be used to control one of several robotic hands available today. The primary application for OTCG technology is for assured ability to service, maintain and operate military aircraft in hazardous environments.

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FOREWORD

In this Report, Orbital Technologies Corporation (ORBITEC) presents the results of the Phase I SBIR effort for the Armstrong Medical Research Laboratory, Human Systems Division, Wright-Patterson AFB Ohio (Contract F41622-89-C-1020) to determine the feasibility of the ORBITEC Telerobotic Control Glove (TCG).

This Final Report discusses the Phase I SBIR research results for an innovative system for telerobotic control of dexterous end-effectors. The OTCG provides control of position and forces applied using the feedback of force and tactile information to the operator. This approach allows for a simple, low-cost, and light-weight controller that may be integrated and used with various dexterous manipulators/end-effectors. The purpose of the Phase I effort was to establish technical feasibility of the OTCG approach.

During the Phase I SBIR effort, various key master controller glove components were designed, built and tested by ORBITEC. Preliminary requirements and design for a prototype glove system were established. Proof of concept feasibility was accomplished through systematic testing of the key components and overall concept analysis and definition.

The results of this Phase I effort provide insight to a point design of the OTCG, which will allow human telerobotic control of a wide variety of robotic end-effectors with appropriate feedback mechanisms. This design also my be easily integrated with existing arm/wrist controllers. The Phase II effort will lead to development of a complete controller system which would be used to control one of several robotic hands available today.

The primary application for OTCG technology is for assured ability to service, maintain and operate military aircraft in hazardous environments. Those environments may include the presence of toxic fuels, chemicals, biological agents and nuclear radiation. Other applications include servicing of Army, Navy, and Marine vehicles and equipment, munitions handling, and some combat applications. It could also applied widely in the subsea and nuclear industries and for servicing satellites in space for the USAF, SDIO and/or NASA. In addition, there is enormous potential for commercial terrestrial applications.

Mr. Ronald R. Teeter, the PI, wishes to acknowledge the excellent work of the project team of highly qualified engineers and scientists that contributed to this effort, including Mr. Thomas M. Crabb, Mr. William L. Phillips, Mr. Dennis E. Bahr, and Dr. Eric E. Rice. The support and encouragement of Lt. Ammon Wright and Captain Ron Julian, Armstrong Aerospace Medical Research Laboratory was also appreciated. The State of Wisconsin Department of Development also supported the project by providing funds for ORBITEC research, ORBITEC equipment acquisition, software development, and University of Wisconsin (UW) support through a technology development loan to ORBITEC. Acknowledgement is also given to UW/Wisconsin Center for Space Automation and Robotics (WCSAR) staff including: Dr. Neil A. Duffie, Dr. Steve F. Wiker, Mr. John J. Zik, and Ms. Karen L. Gale.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

Appendices

TABLE OF CONTENTS (Continued)
List of Figures

TABLE OF CONTENTS (Continued)
List of Figures, Cont.

TABLE OF CONTENTS (Continued)
List of Tables

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1.0 PURPOSE OF THE WORK

In this SBIR report ORBITEC presents the U.S. Air Force with an innovative system for providing control of dexterous telerobotic end-effectors. The ORBITEC Telerobotic Control Glove (OTCG) provides (1) control of position and forces by the operator, and (2) feedback of applied tactile and force information to the operator. By using tactile sensors and stimulators to provide feedback of both tactile and force information directly to the operator, the design of the control system from an interface is greatly simplified. The OTCG, although is being designed as an effective substitute to force reflection, may also be used cooperatively with force reflection to improve human operator performance and capabilities.

1.1 Background

Telerobotic devices have proved their worth many times particularly in the nuclear and subsea industries. However, growth in the application of the devices has been constrained by limitations in dexterity and controllability by human operators. Devices commonly in use today typically rely on two fingered jaw-gripper end-effectors and position and/or velocity control by joy-sticks and other non-anthropomorphic devices. In some cases, force feedback is provided in the form of mechanical backdrive at the user interface.

The problem of providing adequate robot control and feedback of information to the human operator is a difficult one. Even where the robotic manipulator system is limited to a six or seven degree-of-freedom arm with a one degree-of-freedom end-effector, an efficient and effective human interface to the control system is difficult to design. Such interfaces have been designed for subsea, nuclear power plant and other applications. However, these interfaces already saturate the ability of human operators to provide control. The need to develop and control robotic manipulators with multiple degrees of freedom master controllers approximating the dexterity of the human hand, and to provide end-effector sensory feedback to the operator represents a significant technological challenge.

The human hand has more than 20 degrees-of-freedom (4 per digit). However, many of these are not fully independent. Also, in all cases, range of motion is limited (generally around 90 degrees of rotation or less) and, in some cases it is severely limited. A number of robotic dexterous hands have been developed employing three digits. Based on our work and that of other researchers, the hand needs a minimum of three digits and a minimum of two degrees-of-freedom per digit to be able to be used effectively for a broad range of grasping and manipulative tasks. Of particular note is the work of Dr. John Jameson [Jameson, 1987] and his design development, and test of a six degree-of-freedom

prehensor for use as a end-effector on a hard-shell astronaut space suit. Jameson's work demonstrated that a six degree-of-freedom device provided the capability to perform a wide variety of tasks.

ORBITEC's founders (at their previous place of employment) developed, built and tested a modular six degree of freedom dexterous hand [Teeter, 1988]. A key design requirement for this hand was that it be totally self-contained, attachable to virtually any robotic arm with simple mechanical and electrical interfaces. This meant that all of the drive mechanisms (motors, encoders, gears, linkages had to be located within the palm and fingers of the hand. This requirement dictated minimization of the number of degrees-of-freedom and associated drive mechanisms. Our assessment of dexterity requirements for tasks to be performed indicated a minimum of three digits with a total of six degrees-of-freedom would be required. The hand, therefore, was designed according to those constraining requirements. It was a six-degree-of freedom, three-fingered hand with a swivel thumb. Based on these results any dexterous hand controller human interface must be capable of handling at least six-degrees of freedom. In addition, it must be integrable with a six or seven degree of freedom arm/wrist control interface.

Sensory feedback requirements begin with the need for a quality vision and lighting system incorporating multiple camera views and/or stereo vision. In addition, force/torque feedback information from the fingers is needed, as well as conveyance of the sense of touch (tactility) identifying contact with an object and slippage at the hand/object interface. Tactility is also useful in identification of object shape and orientation, and surface characteristics. This latter capability can be extremely important when vision is blocked, degraded or failed. Other sensory information (e.g. auditory) can also be important. As will be demonstrated, ORBITEC's primary interests are in the development of a master controller incorporating force and tactility feedback to the operator.

For the interface between a robot arm controller and human operator, force feedback generally is provided by motors and drive mechanisms integrated into the controller (joy stick exoskeleton, other). The motors backdrive the controller against the operator in proportion to forces being exerted by the robot. This approach works well for the arm and has been implemented by a number of robot arm suppliers (Western Space and Marine, Kraft Telerobotics Inc. and others). However, force feedback for a dexterous hand is much more difficult to implement without remotizers because of the small volume of the hand and the number of degrees of freedom. Viable means of control of dexterous hands with the control interface directly at the fingers of the human operator require mechanical backdrive systems that are currently too large, heavy and cumbersome for basic application. Another approach must be found. The approach selected for the control/operator interface

must be integrable with tactile feedback, and the entire hand control system must be integrable with the arm controller.

ORBITEC's founders have been engaged in research and development in dexterous hand position control, and force and tactile feedback for the past four years. We conceived and organized the Wisconsin Center for Space Automation and Robotics (WCSAR). One major focus of WCSAR is technology to increase robot dexterity and human operator telepresence (Teeter, et al., 1988]. We developed a position control mechanism for the Astronautics dexterous hand which was a light weight aluminum exoskeleton with potentiometers for joint angle measurement. We experimented with motorized force feedback on a single digit finding the concept doable but the device bulky, cumbersome, and heavy. As part of its WCSAR Activities the University of Wisconsin designed an developed several dexterous hand or dexterous finger controller prototypes (see Figure 1 and Table 1). These devices exhibit the same problems of bulkiness, etc. that we encountered.

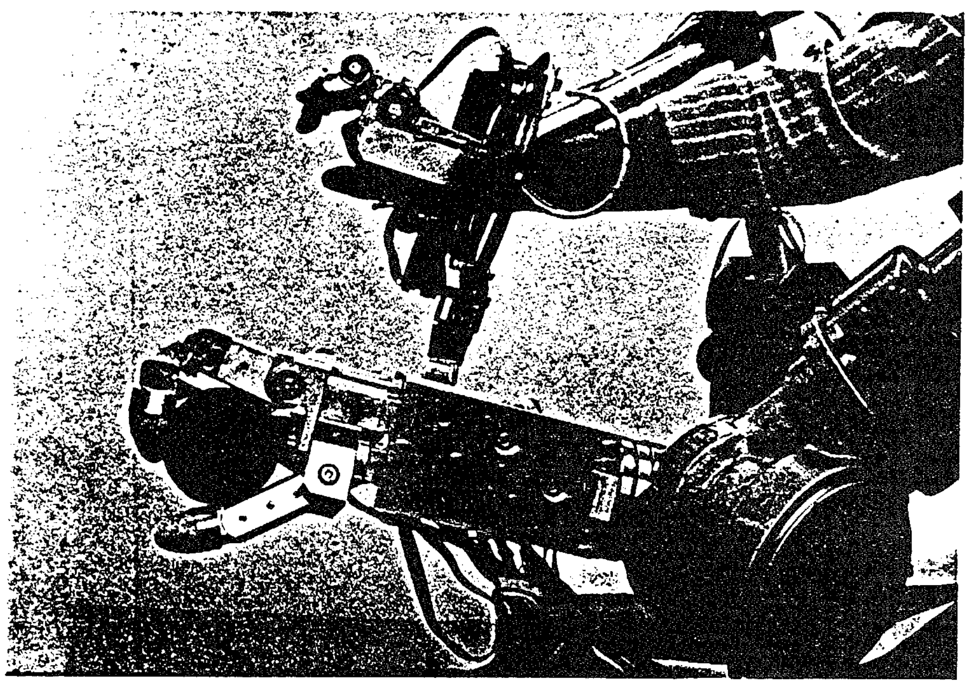

Figure 1. Sample Position Control Master/Slave Prototype

Table 1. Sample Arm/Wrist Controller Developments in WCSAR

Component	Characteristics	Status
Cartesian Coordinate Arm Master (Zik A1)	• Cartesian coordinate configuration with three degrees-of-freedom • Standard industrial interface (RS232 comm. to ASEA)	Complete
Non-Kinematic Replica Master Hand Type A (Zik H1)	• Two digit (finger) device • One degree-of-freedom per digit • Force reflection implemented • Actuators local	Complete
Non-Kinematic Replica Master Hand Type B (Laird H1)	• Three digit (finger) device • Three degrees-of-freedom per digit • Force reflection provided with one drive motor per finger • Actuators local	Complete
Non-Kinematic Replica Master Hand Type C (Laird H2)	• Three digit (finger) device • Three degrees-of-freedom per digit	Complete
Non-Kinematic Replica Master Hand Type D (Zik H2)	• Three digit (finger) device • Three degrees-of-freedom per digit • Force Reflection provided with each degree-of-freedom • Actuators remote	Currently being manufactured
Non-Kinematic Replica Master Hand Type E (ACA H1)	• Three digit (finger) device • Two degrees-of-freedom per digit	Currently being manufactured
Non-Kinematic Replica Master Arm/Wrist (Zik A2)	• Six degrees-of-freedom • Mechanically counterbalanced • Three intersecting axis wrist configuration with hand grip in center of wrist	Currently being manufactured

In a related project for the NASA Johnson Space Center (JSC), we developed experimental tactile sensory and stimulation system for an Astronaut's space suit glove (Figure 2). The need for such a system arises because the glove is cumbersome due material thickness and stiffness and due to fact the glove and entire suit are pressurized in the vacuum of space. The astronaut wearing the suit performing extravehicular activity (EVA) in the vacuum of space experiences a significant loss of the sense of touch. This causes the astronaut to overgrasp to assure a firm grip on objects. The result of this and other factors is that fingers quickly tire limiting and slowing work that can be performed and the astronaut relies heavily on visual feedback. Our system included (1) tactile sensors mounted on the exterior surface of the space suit glove; (2) tactile stimulators integrated with a "comfort glove" currently worn by astronauts inside the space suit glove; and (3) interface electronics with a power supply. Thin, flexible piezoresistive tactile sensors of several different designs were fabricated and tested. Both electrocutaneous and vibratory stimulators were tested. Extensive human subject testing was conducted. The result demonstrated concept and hardware feasibility. The results also

indicated better performance using vibratory stimulators. Thin piezoelectric crystals were shown to perform well as vibratory stimulators [Crabb, 1988].

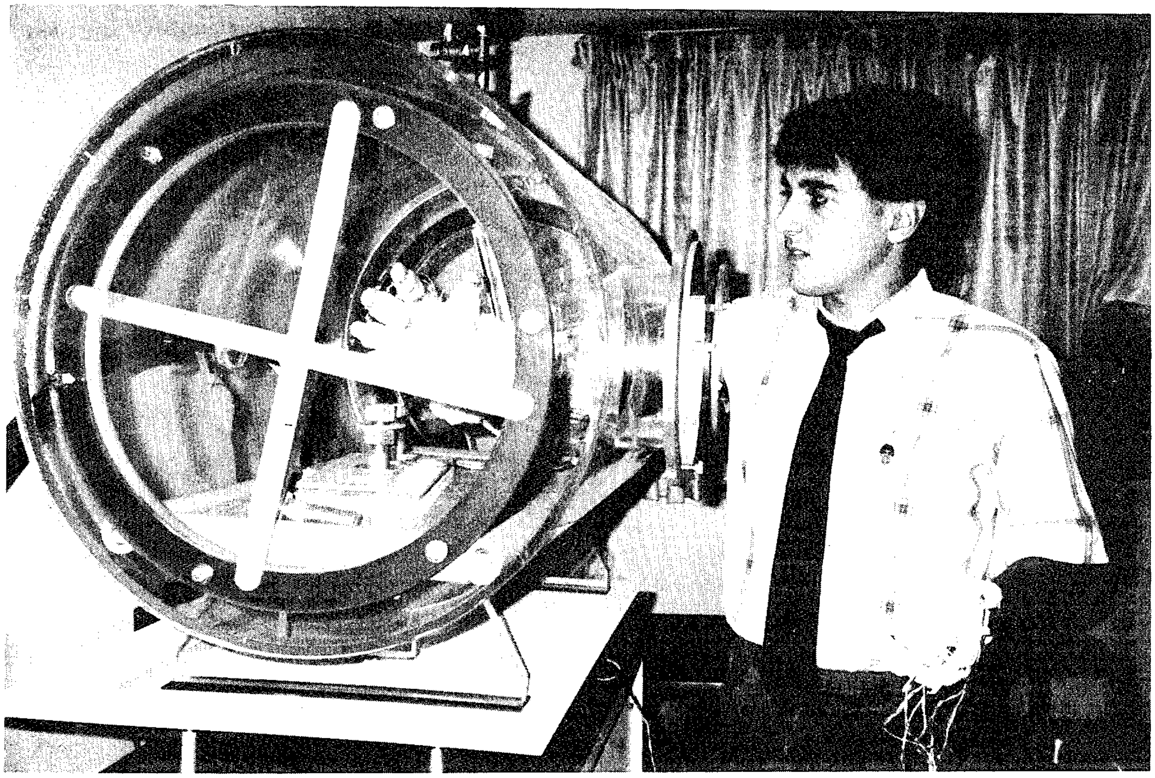

Figure 2. Prototype Tactile Feedback System for the Space Suit Glove

Our interest in tactile sensory/stimulation system originated from our association with the University of Wisconsin. The UW has been experimenting with and developing sensory substitution systems for medical and other applications. Sensory substitution has been researched and applied to persons who have lost or degraded sensory input through normal channels (e.g., vision, auditory, tactility, etc.). In these cases artificial sensors designed to replace the natural sensors and the data converted into a sensory input that is not impaired. For example, a person who has lost the ability to hear may be supplied with a microphone which converts the auditory signals to video in eyes or tactile stimulation (a system is available on the commercial market known as the Tacticon which does the latter). The brain can adapt very well to these sensory substitution techniques with proper training. The concept of sensory substitution which has been proven and demonstrated in the medical applications and in our own research was a key element in the ORBITEC development effort reported herein.

1.2 System Concept Summary

ORBITEC has developed a preliminary laboratory version of a controller to be used by the human operator of a robotic dexterous hand, and used to control the hand. The controller includes mechanical exoskeletal elements and new position monitoring sensors to monitor the operators finger joint angles. It also includes tactile stimulators to provide both tactile and force information to the operator. The controller to be built in Phase II of this SBIR activity will have two modes of operator stimulation. The first would provide tactile feedback information to the operator. This stimulus mode would be responsive to tactile sensors on the robot hand. The sensors and stimulators are provided to be very sensitive to very slight initial contact and a relatively narrow range of response to contact forces (stimulation will peak at relatively low force levels - e.g. less than 10 psi). The second mode of stimulation will be used to provide force and torque feedback information to the operator. This mode would have a higher response threshold (of the order of one pound), and a response range (from zero stimulation to maximum intensity) extending up to 20 pounds or more. This second mode relies more heavily on the principle of sensory substitution.

Normally, tactility in the human body occurs through the lightest of contacts and pressures through sensors in the outer surface of the skin. As forces are increased to the human, these "tactile sensors" saturate and the resultant force/torque vectors are sensed through the limbs and extremities via the reaction of muscles and tendons. In our system, the sense of tactility is transmitted to the operator in a relatively natural way by light vibratory stimulation of the outer skin. As forces increase the tactile stimulators saturate and the second mode of stimulation will impart vibrational stimulations to the skin in proportion to forces/torques measured at the robot hand. The operator will be able to distinguish between the two modes through a change in the vibrational stimulating patterns. Several alternatives exist to provide this multi-mode stimulation such as location of stimulation, intensity (amplitude), frequency, stimulation area, pulsed vibrational input, translational vibratory input, or any combination of the above.

There are a number of compelling advantages to the ORBITEC control glove. First, it provides accurate and reliable control of position and force with tactile and force feedback without the use of unwieldy and impractical mechanical backdrive systems. Second, our approach effectively separates force feedback from force control (feed forward) which greatly reduces the man-in-loop stability problems that plague mechanical backdrive force feedback (particularly force reflection) systems. In the mechanical force reflective systems, these problems are aggravated by the crosscoupling of force and position control inherent in backdriven systems. Third, the ORBITEC approach provides a robotic dexterous

hand controller that is usable with a integrable with existing robot arm controllers. Finally, the ORBITEC product can be used as a substitute for or in a complimentary mode to the force reflective systems to enhance human teleoperator performance.

For the Phase I SBIR effort, ORBITEC designed, built and tested master controller glove components. We also developed and carried out a proof of concept demonstration that established concept feasibility and worth. Finally, we developed a design for a prototype glove system. In Phase II we will build and test an integrated system prototype.

1.3 Technical Objectives

Automation and Robotics (A&R) technologies have been the focus of much research and development in recent years to increase operational productivity and capability in several areas. One sector of developments have focussed on "human-in-the-loop" control and operation of remote robotic "slaves". These "telerobotic" systems may be very useful in situations that present danger to humans or difficult access by humans (e.g. hazardous nuclear, chemical, and biological contaminated environments; space; deep sea; nuclear plants), and have complex nonrepetitive operations that are difficult to automate. Flight line maintenance is one example of such a "unstructured" environment [Julian, 1988]. Several other telerobotics applications exist for the Air Force [e.g., Anderson, 1986]; Army [e.g., Bibb, 1987] and the Navy [e.g., Riseman, 1986; Kinchang, 1986; Hill, 1985]. Telerobotics may also be used as a precursor to automation and may contribute to the teaching of complex automated procedures. Several telerobots to date have followed anthropomorphic design to minimize the physical variances between the human operator and the telerobot slave.

Feedback of information about the robot position, tactile and force status to the human operator is required for proper control of the telerobot. Such feedback may take advantage of all human sensory input. To date, vision has been the principle feedback mechanism and remains the most effective. However, it has been shown that increased feedback of tactile, force and torque information can significantly reduce the dependence of vision and increase productivity, accuracy, and capability. Much of the research and development to date has concentrated on the sensors for tactility and force/torque detection but little has been accomplished to provide adequate feedback of that information to the human operator. Providing adequate information to the human operator including position, force/torque, and tactile feedback has added to the complexity of the telerobotic system and has contributed to some of the control loop problems. Many of these problems relate to the coupling of the force/torque and tactile feedback with the position control components. The ORBITEC Telerobotic Controller Glove (OTCG) alleviates many of the control loop problems by providing operator information directly through

sensory substitution which decouples the position control and the force/torque reflection components of the system.

The OTCG combines state-of-the-art position control into an operator glove which also contains independent modes of information display to the hand for force/torque and tactile feedback. These latter informational displays utilize stimulus to the skin through vibration using piezoelectric crystals and metallics. Electrocutaneous approaches were also investigated; however, the technology is not sufficiently developed for consistent and comfortable feedback to the hand [Crabb, 1988]. A tactile feedback system has been prototyped to augment the tactility of the space suit glove [Crabb, 1987; Crabb, 1988]. Because of the efficient response of the skin to vibration, the piezoelectric and some electromechanical devices can be excited at lower voltages than that used for acoustics or large displacement vibrations; thus high voltages are not required for the crystals. These devices are not extremely complex and the electronics can be packaged into a glove-sized device.

Research at the University of Wisconsin and by the key personnel of ORBITEC have demonstrated that human adaptation to sensory substitution input is quick to learn, can be unconsciously internalized, and has high retention. In other words, with little training the operator can interpret the stimulus being received through the glove with high accuracy and efficiency in just a matter of days. Further, that skill, once learned, is retained for a long period of time.

The OTCG configuration will allow human control of almost any robotic system. This includes very dexterous robotic hands such as the MIT/UTAH anthropomorphic hand. Tactile and force/torque sensors are being considered for this end effector [Jacobsen, 1987; Li, 1989]. The OTCG will contain up to 16 degrees of freedom as needed and provide feedback of tactility and forces/torques through sensory substitution methods. Various joints can be reprogrammed for use with robot hands with only a few degrees of freedom.

Specific technical objectives for Phase I efforts for development of the ORBITEC Telerobotic Controller Glove (OTCG) were to demonstrate key components and specify the design of the OTCG to interface with any robotic device. Three technical tasks were organized to conduct component-level research and development, develop systems level design, and to demonstrate and test key components and designs. These Phase I efforts have contributed to the demonstration of key component technologies and have supported the planning of the entire OTCG system development and testing in Phase II.

The key objectives of the component-level research and development included the development of stimulator prototypes and position control devices which could be integrated into the glove.

Also, research and development of existing flexible tactile sensors was continued and applied to force/torque applications. Alternative designs based on existing prototypes and experience for each component were investigated and integrated into the design decisions of the Phase I prototype developments and tests. For example, a working prototype existed which provides vibratory stimulation from the hand for tactile feedback; however, additional work is required to develop stimulation channels to the hand for tactile feedback and force/torque feedback through different frequencies, locations, and other parameters.

The specific objective of the system design task was to address alternatives of design for the overall OTCG system. Areas addressed included the mechanical design of the glove, interface design options, electronics and control driver development. Each of the component technologies were integrated into the system design. An overall design is recommended for development in Phase II.

The specific objectives of the demonstration and test task were to provide data which allows estimation of the performance of the OTCG components and guide the development of the overall design. The output of this task will includes measurands used in evaluation of the components technologies and the overall system, a demonstration of the key component technologies, and a test/evaluation of the components. Thus, this task will provide the direction for development and the proof of feasibility.

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2.0 DESCRIPTION OF THE WORK CARRIED OUT

The work performed in this project focused on the design and development of the ORBITEC Telerobotic Control Glove (OTCG) system, primarily for the purposes of SBIR feasibility demonstration. The work addresed the general architecture, sensors and stimulators, required interface devices, and component and system testing.

The overall approach to the development of the OTCG is simplicity of design through the decoupling of the tactile and force/torque feedback from the position control components. The control loops for each of these functions then will be closed through the human operator and not through a combination of the mechanical controller and the human operator as most controllers in the past have been designed. This approach both reduces instabilities in the system and simplifies the system design.

The project tasks are described below include: (1) component research and development, (2) integrated system design, and (3) demonstration and test of the key component technologies. Each of these tasks will provide proof of feasibility and direction toward an operational OTCG system which will be developed in Phase II.

2.1 Component Research and Development

The key objective of this task is to assess component alternatives to existing prototypes and concepts for demonstration/testing and for integration into the ORBITEC Telerobotic Controller Glove (OTCG). The key components requiring research and development are: (1) stimulators; (3) tactile and force sensors; and (3) position control devices.

1. Stimulator. The stimulator device is a vibrating transducer placed within the master glove to provide feedback of tactile/force information to the operator.

2. Force/tactile sensor(s). This sensor (or combination of sensors) provides signals indicating the force applied by the slave effector. It may be either a single sensor or a combination of two sensors indicating touch and force magnitude information.

3. Position control. The position control subsystem must detect the relative angle of finger joints of the operator's hand via the master control glove. It is used to provide position control signals to the slave controller.

2.1.1 Stimulators

The ultimate goal of the OTCG is to provide a communication link between the telerobotic operator and the telerobot. Except for the potential of complementary visual input, the stimulators

of the OTCG are the primary human-machine interface for delivery of tactile, force and torque information from the sensors on the telerobot to the human operator. The information collected and transmitted to the operator generally corresponds to light tactile forces, normal and shear forces, and torques. The stimulators are simple, lightweight devices that could, at a minimum augment force reflection; but proposed here to obviate the need for a complex, massive and power consumptive force reflection system.

ORBITEC personnel have developed and applied stimulation devices for augmentation of tactile information for both robotic applications and the NASA Space Suit Glove (shown in Figure 2). Both electrocutaneous and vibratory stimulation concepts were evaluated in the laboratory in a variety of configurations including a glove. With technologies available to date, vibratory stimulation, through use of piezoelectric materials, has been found to be more effective and reliable than electrocutaneous [Crabb, 1988]. Several sources of piezoelectric devices exist [Penwalt, 1983; Star Micronics, 1985; Vernitron, 1987; Piezo Systems, 1987]. Experimenting with off-the-shelf components low AC voltages (-15v to +15v) have successfully been applied to piezoelectric crystals at frequencies which match the optimum response of the human receptors to yield perceptible feedback. This prototype provided some degree of linear range and required little power to the feedback stimulators [Crabb, 1988].

Developments key to this component include (1) choice of appropriate stimulator technology that can provide adequate resolution and dynamic response, (2) the location and configurations of the stimulator devices in the glove; (3) provision of two to three modes of stimulator feedback to accommodate tactile (already demonstrated), force, and torque sensory inputs, (4) configuration of the stimulators to adequately display torque information, (5) provision of a standard interface such that any sensor can be configured to activate stimulator response. ORBITEC Personnel have investigated several technologies and configurations hand stimulation including electrocutaneous and vibratory. Human perception of either vibrating and electrocutaneous stimulation has resolution limits for various parts of the body [Weinstein, 1968; Velund, 1970; Gescheider, 1983]. Also, incremental productivity increases of the telerobotic system (including the operator) become smaller as resolution increases and the system complexity increases. Thus, there exists a trade-off of system resolution, productivity, and complexity which must be investigated. The size of the stimulators is directly related to the desired resolution and will be determined by this trade-off. Piezoelectric crystals, with the applied AC voltages have the potential of being configured in arrays with relatively high resolution, whereas piezoelectric films (e.g. bimorphs) require higher voltages and larger areas for deformation.

The various modes of feedback may be provided through

different frequencies, amplitudes, modes of stimulation or some combination of these. Parameters of the human vibratory response capability are summarized in Appendix B.

Torque may be displayed by a translatory stimulation in the direction of the torque. The interface can be standardized to a specific voltage input range for the available stimulators allowing for different sensor-to-stimulator mappings. Alternative designs and configurations have been assessed for this component and iterated with the OTCG system design in Task 2, and demonstrated/tested in Task 3.

2.1.1.1 Stimulator Options and Alternatives

Force and touch information is to be conveyed to the operator by means of vibration stimulators located in the master control glove. Each tactile/force sensor on the slave end effector will be directly mapped to a corresponding stimulator in the glove. As described in a later section on system design, both touch (low range) and force (high range) data will be presented via a single stimulator.

Stimulators considered for this function must be small in size, require only relatively low operating voltages for safety reasons, and provide localized stimulation. Prolonged use of the device must not produce reduced sensitivity or operator fatigue. For greatest sensitivity of the operator, the stimulator should operate in the 100 to 1000 Hz range with an optimal response in the 250 to 300 Hz range.

Two classes of stimulators were investigated during this effort: electromechanical and piezoelectric. Each is discussed below.

2.1.1.1.1 Electromechanical Stimulators

Electromechanical stimulators utilize electrical current to drive movement of a contact device through a magnetic field. The electromechanical stimulators considered consist of a small solenoid with a moving iron core. The core is spring loaded so as to be retained within the coil and is forced to extend beyond the coil when a pulse of current is applied. The movement may be mechanically amplified with the use of levers. An example of this type of device is the print head used in dot matrix printers.

One such print head, used in demonstration, is approximately 0.25 inch diameter by 0.3 inch in length. It operates at approximately a 3 volt signal level and at frequencies up to almost 1 KHz. The solenoid core moves a spring loaded lever arm ending in a small pointed print hammer. This configuration is not suitable for use directly as a stimulator because the small contact point (hammer) rapidly causes operator fatigue and localized

discomfort. However, it is possible to increase the size of the contact area to reduce this effect. The major problem then becomes one of physical size.

An alternative is to directly control the movement of the internal pin through the coil current and have the pin directly contact the finger surface through the glove. A sinusoidal or flattened sinusoidal impact could then be utilized to minimize fatigue and deliver a high amplitude vibrational input. As shown in Figure 3, it may be possible to develop a new type of stimulator array based on a printed coil technology. This approach would use a number of layers of printed conductors sandwiched together to form an array of coils with a printed ferrous core within each. By changing the current through a coil or by changing the number of coils energized, the printed layers could be made to expand or contract, thus supplying a localized tactile stimulation at each point within the array. No preliminary calculations or experiments have as yet been conducted. However, if this approach would prove successful it could offer a significant advantage over other available methods.

The preferred alternative electromechanical stimulation concept that can be developed from off-the shelf components contains a single solenoid per stimulator. A rough schematic of the stimulator is shown in Figure 4. Each solenoid has a diameter of 8 mm such that a 3x3 array of stimulators may be possible in a square inch which may fit on the fingertip. Arrays of various sizes may be developed for other surface areas of the hand or other parts of the body. Additional developments are required to maximize the solenoid activation efficiency, and mounting of the arrays. An initial prototype built by an ORBITEC Associate has shown that an amplitude resolution of six levels is possible with minimal or no training. This concept has extremely high potential to create better dynamic responses in more dense resolution arrays than other alternatives which will allow more versatility in providing a wider range of stimulation and stimulation modes.

2.1.1.1.2 Piezoelectric Stimulators

Piezoelectric materials exhibit a mechanical deformation in response to an applied electric field. This change in size is usually quite small (on the order of microinches) but response is typically very rapid (up to tens of kilohertz). The piezoelectric materials may used directly but generally do not provide enough dynamic response. The piezoelectric material may be attached to a resonant substrate such as brass or other metal plate which leverages and amplifies the small piezoelectric deflections for larger vibrational input. The combination of piezoelectric and metal plate provides a mechanical amplification of the magnitude of the motion, greatly increasing size change over the microinch ranges provided by the material itself. These devices are commonly used as audio transducers.

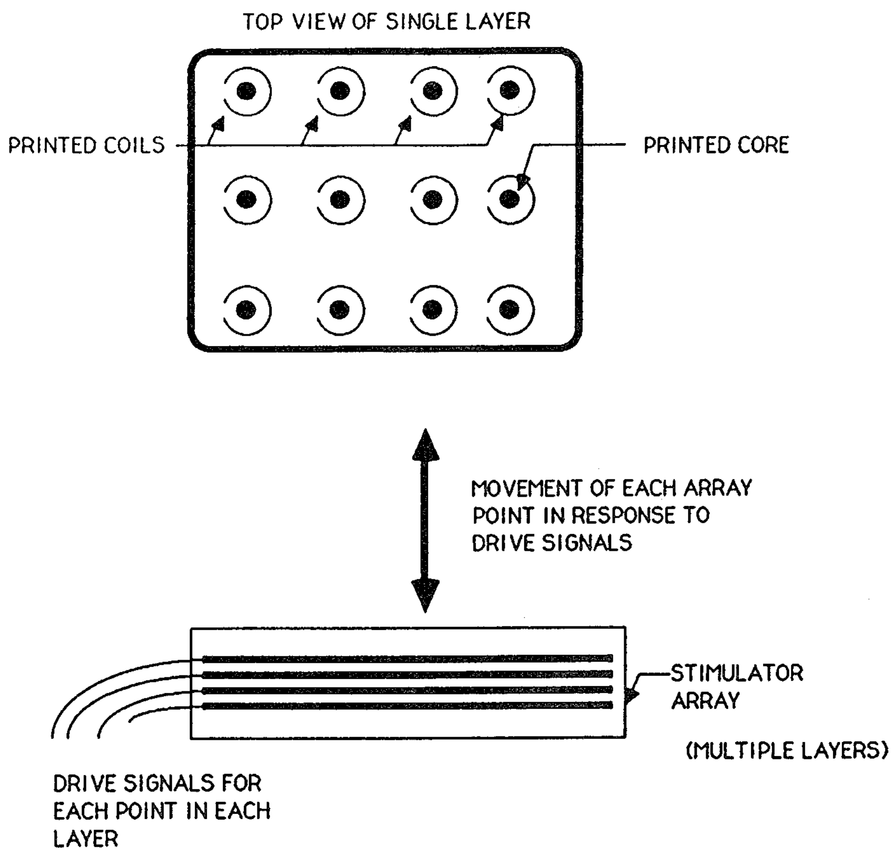


Figure 3. Thin Film Solenoid Stimulator

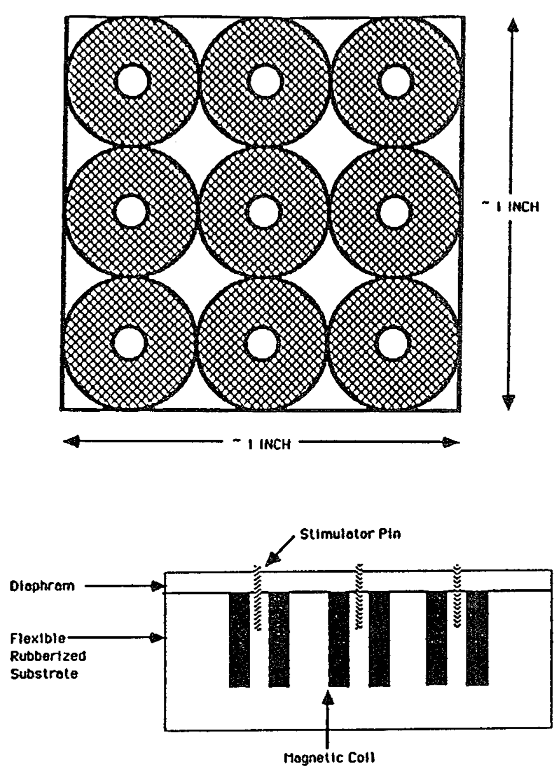


Figure 4. ORBITEC Solenoid Stimulator Array Schematic

Piezoelectric Ceramics

Piezoelectric ceramics are generally applied to polycrystalline materials made from $Pb(ZrTi)O_3$. Initially, these mixtures form a non-piezoelectric crystalline structure; however, at high temperatures when an electric field is applied, the crystal structure organize into a cubic paraelectric phase which becomes polarized by the electric field. The resultant material when cooled demonstrates piezoelectric properties. Such properties such as linear response to electric fields of mechanical stresses are maintained as long as the initial polarizing electric field and formation temperatures are not exceeded. For some applications small quantities of strontium, barium, calcium, or trivalent rare earth elements (Y_2O_3, La_2O_3, Nd_2O_3), Sb, Bi, W and other elements are added to sightly alter some of the piezoelectric properties such as permittivity, coercive force, temperature characteristics of the resonant frequency. Typical physical characteristics of some piezoelectric ceramic materials are shown in Table 2a.

A popular piezoelectric transducer is made from a layer of piezoelectric ceramic mounted to a circular plate substrate and polarized along the width dimension. A sample of existing devices are shown in Figure 5. The device used in prototyping test have a diameter of approximately 0.8 inches, thickness of 0.015 inch thick, and an crystal surface of approximately 0.5 inches in diameter. This device exhibited detectable vibration at levels as low as 4 volts, peak-to-peak and operated over the necessary frequency range. Several alternatives and approaches were and continue to be investigated to decrease the size and increase the dynamic response. It is anticipated that a low power stimulator on the order of 0.2 inch diameter could be developed.

Several of these commercially available piezo ceramic disks were analyzed for response. The smaller of the ceramic disks was originally designed as the source of acoustic vibrations at a resonant frequency of 4.2 kHz. The stimulator has a tin circular disk substrate about 1.2 cm in diameter that is one of the electrodes; and a crystalline layer about 0.8 cm in diameter (see Figure 5a for a schematic representation of this device). The crystalline not centered with a high tolerance but does not seem to affect performance. Section 2.3.1 discusses the tests and results on the various stimulators and configurations.

Piezoelectric Polymers

Some polymers demonstrate piezoelectric properties such as polyvinyl chloride (PVC), polyvinyl fluoride (PVF), difluor polyethylene (PVF_2), and others. The polymer foils are prepared in the same manner as the crystalline structures in that they are heated and a polarizing electric field applied.

Table 2 Typical Piezoelectric Properties

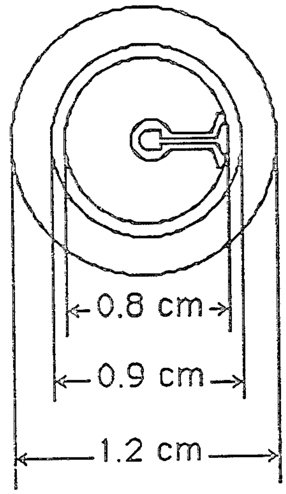
a. Elastic Piezoelectric and Dielectric Coefficients for Selected Piezoelectric $Pb(Ti,Zr)O_3$ Solid Solutions. [Zelenka, 1986]

Characteristic value		PZT (Clevite Corp.)	VIBRIT (Siemens)			PKM (Tesla)
		5	525	668	200	13
Elastic compliance $[10^{-12}\ m^2 N^{-1}]$	s_{11}^E	16.4	15.7	14.3	11.1	9.7
	s_{12}^E	-5.7	-5.9	-5.4	-4.4	-2.9
	s_{33}^E	18.8	19.3	18.4	12.1	9.9
	s_{55}^E	47.5	46.0	42.0	27.0	25.3
Piezoelectric strain $[10^{-12}\ C\ N^{-1}]$	d_{31}	-171	-190	-230	-80	-59
	d_{33}	374	420	565	170	158
	d_{15}	584	625	730	220	199
Relative permittivity	$\epsilon_{11}^T/\epsilon_0$	1730	2000	3300	900	1026
	$\epsilon_{33}^T/\epsilon_0$	1700	2000	3500	1030	1195
Density	$[kg\ m^{-3}]\ \varrho$	7700	7700	7800	7700	7600
Mechanical quality	Q		100	40	1500	2046
Coupling coefficient	k_p		0.64	0.62	0.46	0.32
	k_{31}		0.36	0.35	0.25	0.19
	k_t		0.50	0.50		0.45
	k_{33}		0.72	0.70	0.51	
	k_{15}		0.69	0.66	0.47	0.42

b. Magnitudes of the piezoelectric and Pyroelectric Parameters for Selected Polymers. [Zelenka, 1986]

Polymer	Piezoelectric strain $[pC\ N^{-1}]$			Pyroelectric coefficient p_3 $[\mu C\ m^{-2} K^{-1}]$	Permitivity $\frac{\epsilon_{33}}{\epsilon_0}$	$\frac{p_{33}}{\epsilon_{33}}$ $[\mu C\ m^{-2} K^{-1}]$
	d_{31}	d_{32}	d_{33}			
PVF - β	20-30	2-3	-3	30-40	10-15	2-4
PVF - δ	10-17	1-2	10-15	10-15	10-15	0.7-1.5
PVF	15-30			10-18	5	2-3.6
Nylon 11	3			3-5	4	0.8-1.3
PVC	0.5-1.3			1-4	3	0.3-1.3

a) Small, Thin Substrate
Resonant Frequency for Acoustic Output: 4.2 ± 0.5 kHz
Operating Temperature: -20° to 60° C



b) Large, Rigid Substrate
Resonant Frequency for Acoustic Output: 2.8 ± 0.5 kHz

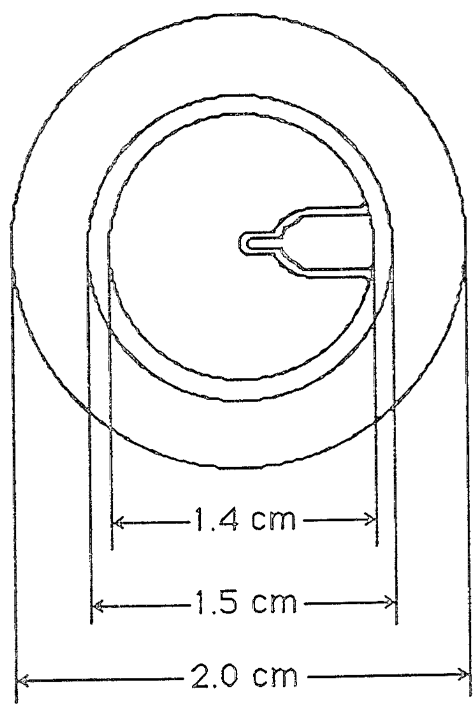


Figure 5 Schematic of Piezoelectric Crystal Mounted on Circular Substrates (Acoustic Buzzer Configuration)

These piezoelectric materials are available in a variety of constituents, sizes and shapes. However, the main use of their materials is in ultrasonic and sonar devices operating at high voltages and power levels. Most of this material is not really suitable for use at low voltage levels as a stimulator. One of their products, a Bimorph, consists of two bonded strips of materials. These will exhibit relatively large motions, but are physically on the order of 0.25 inch in width by 1-1.5 inches in length, making them too large to use for localized stimulation.

Piezoelectric polymer films have the advantage of being flexible and may be fastened to the inside of a glove and still conform to the operator's finger. However their displacements and dynamic response can be easily damped by minimal pressures against the fingers.

2.1.1.2 Location and Configuration of Stimulator Devices

The stimulators are anticipated to be sized to accommodate several per finger as is shown in Figure 6. The glove will provide consistent contact between the stimulator and the skin. The size of the stimulators is currently shown to be versatile for several size hands (see System Design section for details on the glove sizing, and interfaces). This configuration can support the transfer of tactile, force, and torque information in modes which will be described in the following section. Testing will be required to determine perceived resolution as opposed to delivered resolution and to understand the system performance implications of such resolution (see Section 5.0 for further study recommendations).

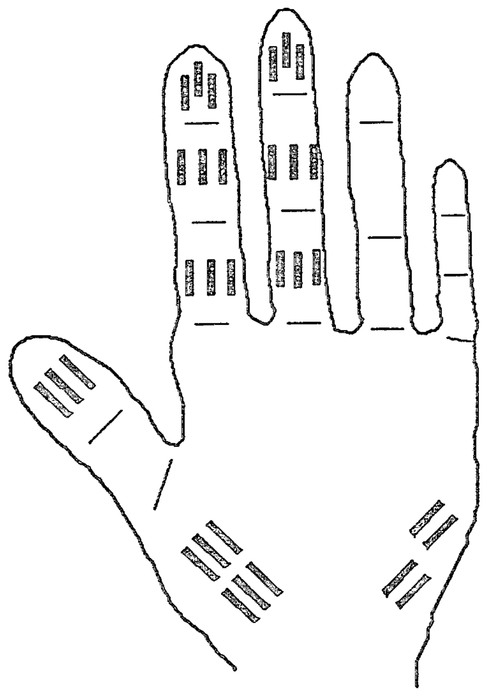
Other potential configurations include stimulator locations on the top of the hand and on the side of the fingers.

Over 16 configurations of stimulator devices were assembled for preliminary response testing. Pictured in Figure 7, all of these prototype configurations used the small piezoelectric ceramic disks (discussed above) with alternative mounts. Some of these mounts are applicable hand controllers with a rigid surface for the finger to control position of the slave telerobot.

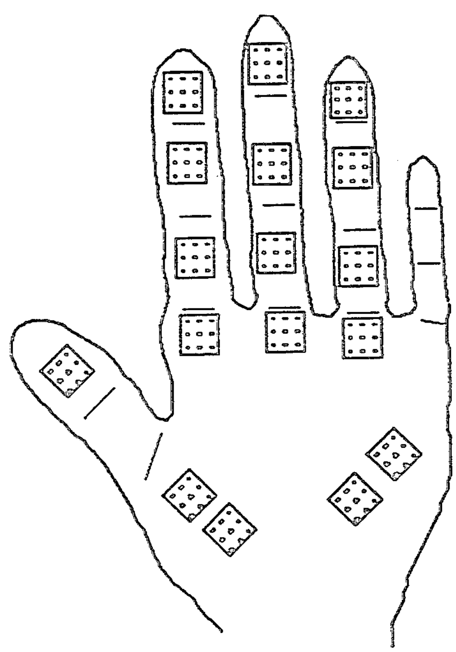
2.1.1.3 Multimode Stimulator Feedback to Provide Tactile and Force Information

Forces experienced at the slave end-effector of the telerobot can be classified into normal, shear, and torque. Rarely is a pure torque experienced without being accompanied by normal and/or shear forces unless the torque is being translated "internally" to the end-effector through the wrist and arm. Thus, although torque information display feasibility will be discussed, the OTCG will concentrate on displaying normal and shear forces to the operator that are directly acting on the end-effector. The OTCG will allow

for a rigid or semirigid connection to the arm/wrist controller so that the appropriate "internally" torques may be transmitted.

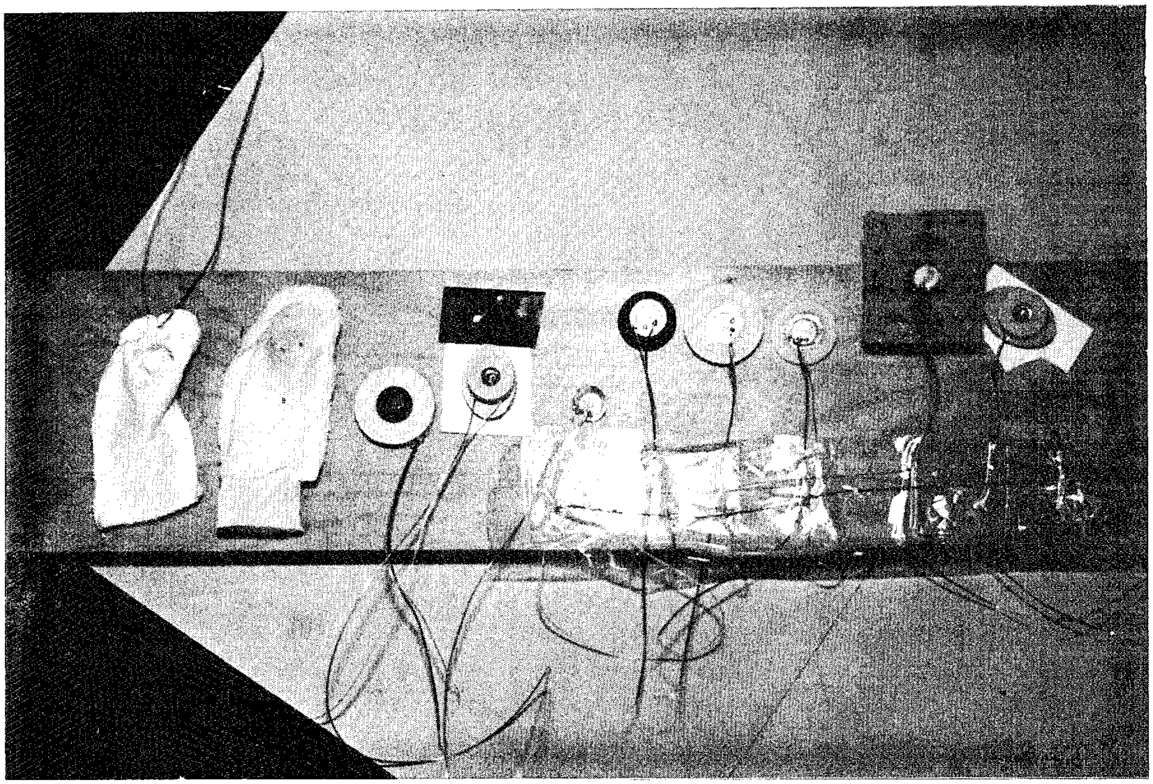


a. Piezoelectric Crystal Stimulators



b. ORBITEC Solenoid Stimulator Arrays

Figure 6. Currently Recommended Stimulator Locations



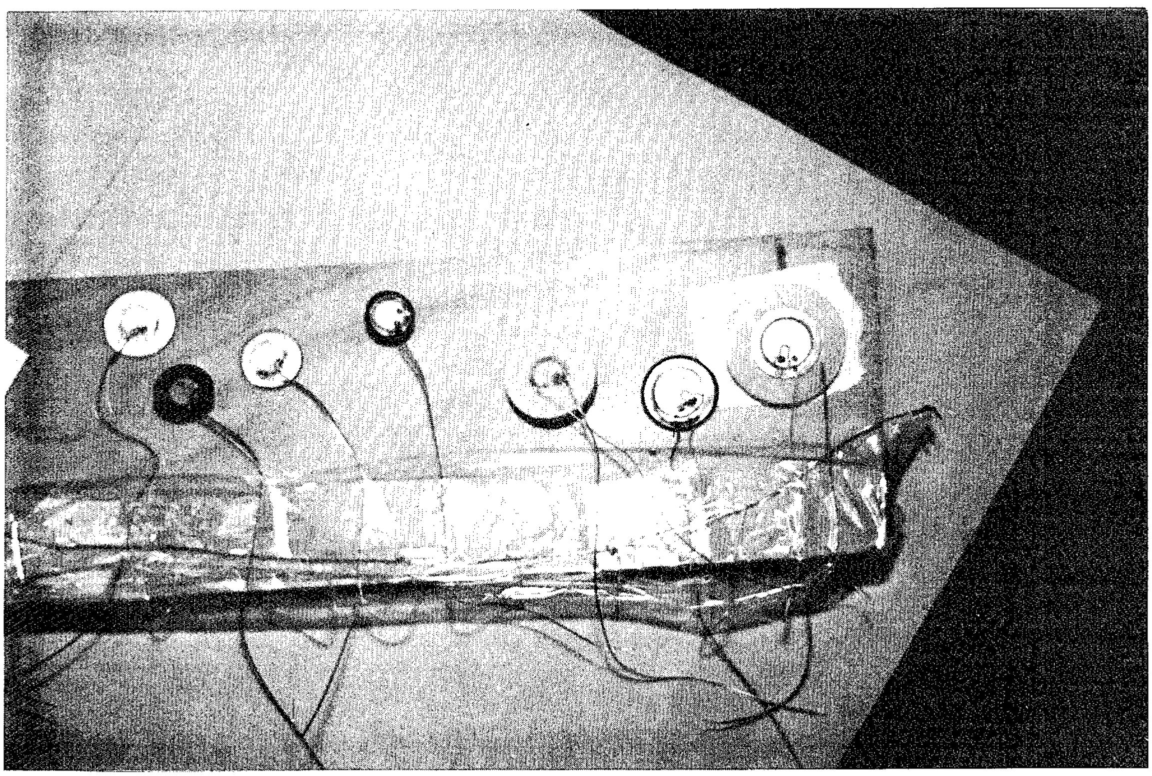


Figure 7. Some Stimulator Mounting Configurations Prototyped

2.1.1.3.1 Normal Force Information Display

It is desireable to combine both the tactile regime (0.0 to 0.75 pound) and force regime (0.75 to 5.0 pound) information into a signal for one stimulator. To provide a wide dynamic rage for both tactile and force regimes and because the tactile range represents such a small percentage of the overall force range desired, independent tactile and force stimulator modes have been considered.

Several parameters must be investigated as to their effect on the gradient response of the perceived vibratory input levels. the most critical parameters include:

- vibratory amplitude
- vibration frequency
- area of vibration
- pulsed frequency of vibratory stimulus
- mechanical impedance between the skin and the stimulator

Many of the single variable gradient responses have been investigated in the past. From the existing literature and from experience with the vibratory stimulation, ORBITEC feels that a combination of these parameter will provide the best operator interpretation of the sensor data. Two examples of combining the various parameters are demonstrated below. Much more complicated schemes are possible; but have not been investigated under the scope of this contract.

The first alternative is to vary amplitude from 0 to full dynamic range at a low frequency (e.g. 100 Hz) and transition the frequency variance for the force range as shown in Figure 8. This was our first approach; however, preliminary indications are that the overall perceived vibrational energy delivered to the skin is the important parameter. Although no detailed research has been done or is available on the reception efficiency of the skin to vibration at various frequencies (maximum response at 250Hz to 400Hz) and amplitudes, the perceived vibration is a function of both frequency and amplitude and thus the two control parameters could not be treated and independent sensory inputs. We hypothesize that both frequency and amplitude may be used to vary the perceived vibrational input level and may be combined to drive the stimulator from low perceived levels to maximum perceived levels avoiding fatigue at the higher levels.

The second and preferred alternative provides for separating the tactile and force regimes into input modes that relate to perceived amplitude and pulsed frequency as is shown in Figure 9. In the tactile range, the amplitude would be fixed at maximum but be pulsed from a fast rate (e.g. 30Hz) to a slow rate (e.g. 1 Hz). The ability of the skin to determine on/off switching of the vibrational response is very acute and thus make this input

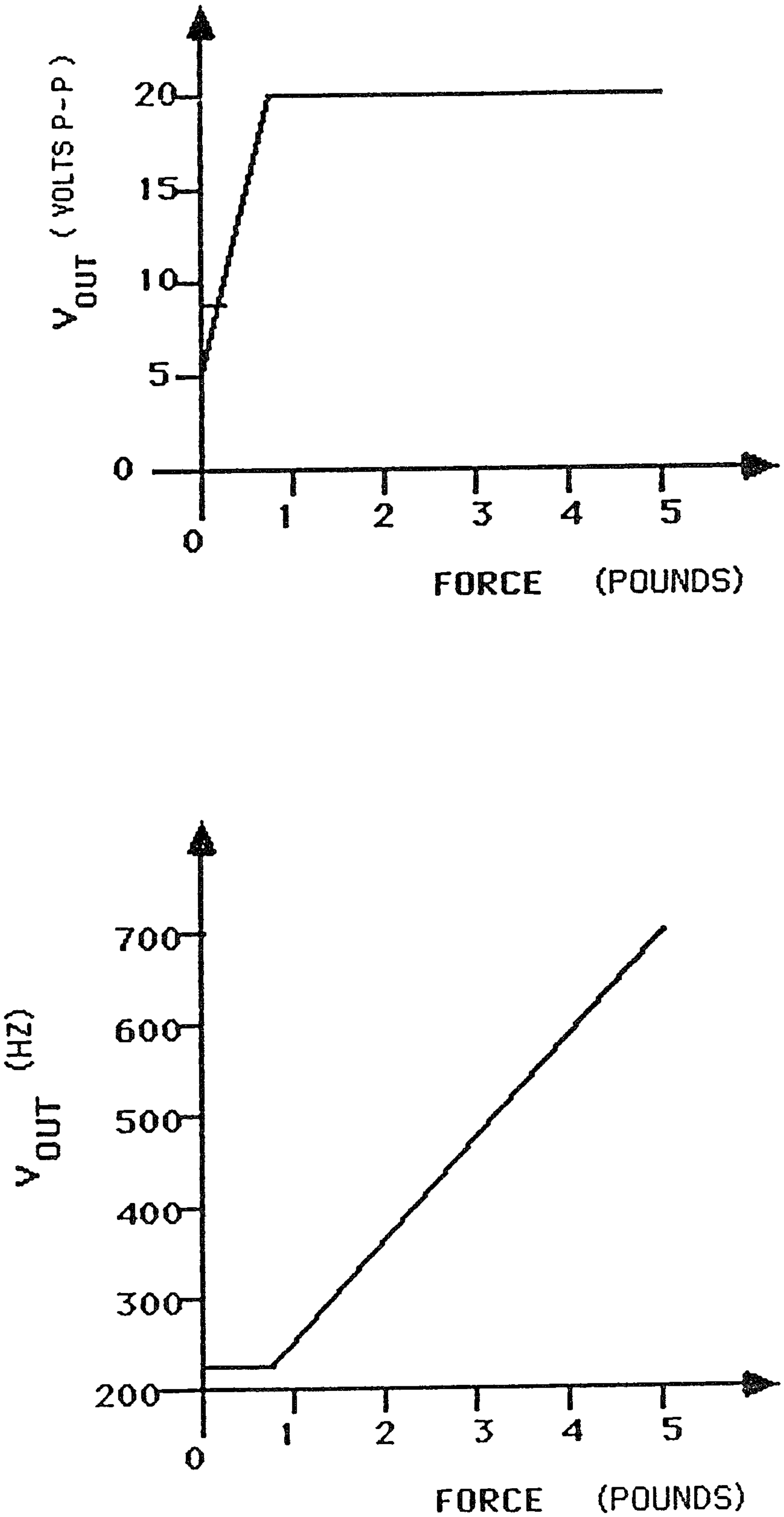


Figure 8. Sample of Frequency-Amplitude Mode Stimulation Transition

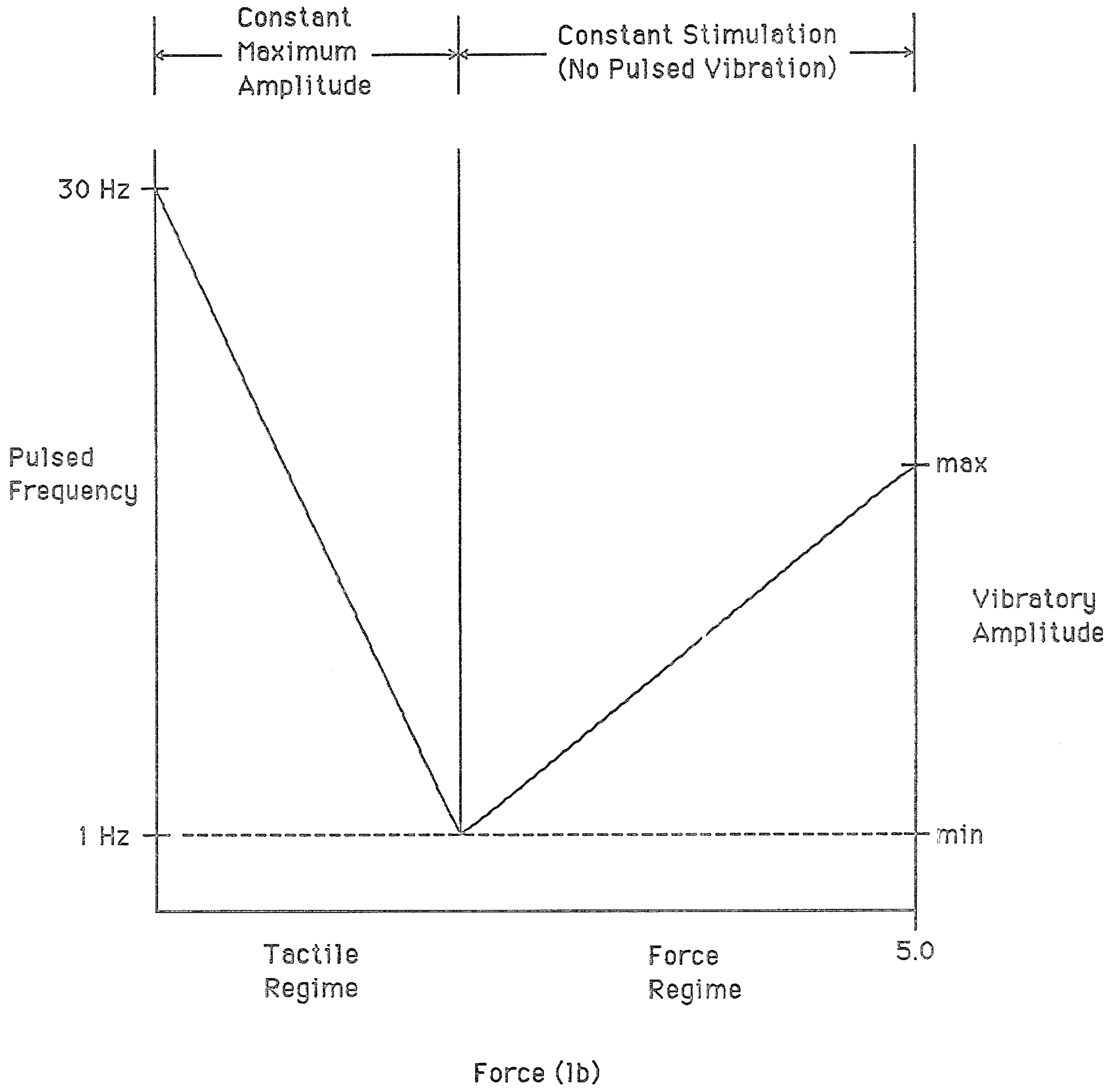


Figure 9. Sample of Pulse-Amplitude Mode Stimulation Transition

modality quite efficient. The reason for the higher pulse rate at the low end in the tactile range is to warn of potential slippage or loss of touch. In the force range the signal would be continuous but range from a perceived low amplitude to high amplitude. The range in perceived amplitude would be accomplished by varying both frequency and input waveform amplitude as discussed above. Thus, to maintain a significant grip, the operator would hold an object trying to minimize the vibrational input and would be warned of a lessening grip by higher pulsed frequency and of overgripping through high amplitude constant vibrations. Some operator training is anticipated to properly interpret this input; however, this training is estimated at less than 30 minutes based on current evaluations conducted.

2.1.1.3.2 Shear Force Information Display

Shear forces can be very important in gripping and manipulation tasks as they represent the potential for slipping and movement of objects along the surface of the slave telerobot. Shear force information displays could be represented by an additive display mode to the normal force display or be represented by a translational stimulation in the direction of the shear force. The additive display mode would not typically give a direction of the shear force. The translational stimulation does give a direction but requires a two dimensional stimulator array with fairly high perceived resolution. The Small Piezoelectric Arrays or the Simplified Solenoid Stimulator Array may provide adequate resolution for the display of shear forces. Testing is still required to determine appropriate array resolutions that will give the operator an interpretation of shear.

2.1.1.3.3 Torque Information Display

As mentioned above, pure torques are rarely without associated normal and shear forces. If pure torque sensors are available however, the torque information may be displayed directly as (1) a translatory vibration in a circular pattern across the stimulator arrays with the center of the circle approximating the axis of the torque, (2) a translatory stimulation across several arrays which would include the back of the hand, or (3) a combination of the stimulation modes identified in the discussion of normal force displays. Another mode in which to indirectly display torques would be provided by the arm/wrist controller through a rigid or semirigid connection between the arm/wrist controller and the OTCG. Currently a rigid connection is planned.

An example of the circular translating stimulation may be illustrated with the Fingertip sensor (See Section 2.1.2) and the 3x3 solenoid stimulator array. The fingertip sensor has the ability of resolving an applied force into three orthogonal normal forces and a torque along the major axis (see upcoming Figure 14). The torque resolved by the finger would be mapped into the

circulating stimulation on the operator fingertip using the outside points of the stimulator array.

Another example of translating stimulation to directly display torque information through the OTCG is the use of arrays on the multiple sides of the finger/hand. The same torque resolved by the fingertip sensor could be displayed by a stimulation that traverses the circumference of the finger using several stimulator arrays.

Finally, a third mechanism for displaying torque utilize another mode of stimulation that would be additive to the other normal and shear force modes. An example would be the use of a frequency shift in the vibration of a few stimulators to locate the center of the torque; lowering of the frequency may correlate to a negative torque and an increase in the frequency may correlate to a positive torque. This type of display would require extensive testing to determine whether operators could properly interpret the various modes of stimulation. Although a very feasible display (from parallel research in sensory substitution techniques), a significant amount of training may be required for the operator to be able to gain significant information from this type of display.

2.1.2 Tactile and Force Sensors

Research and development of sensors, although not directly related to the OTCG for display of information, provided insight into the types of information to be displayed and provided interfacing testing apparatus for the OTCG. ORBITEC has reviewed several types of sensors available on the market and being developed. We have concentrated our own developments on the Fingertip sensor and potential evolutions, and the piezoresistive flexible membrane sensors. Both sensors provide a good response in the tactile range. General types of sensor are discussed followed by more detail on the fingertip and the piezoresistive sensors.

2.1.2.1 Tactile and Force Sensing Options

Tactile and force sensors are to be mounted on the slave end-effector to indicate a sense of touch and magnitudes of applied forces. Different sensor types have the ability to measure different types of forces in different magnitude ranges. Available sensors typically fall into three overlapping categories: proximity, tactile, large normal force, shear force, and torque sensing. Some sensing technologies can accomplish more than one type of sensing.

Proximity sensors which give an indication when the sensor approaches an object without requiring actual physical contact. These are not the desired type for this application and are beyond the scope of this report.

A tactile sensor may be thought of as an extremely sensitive sensor (possibly a simple on-off switch with a low activation level). In the very light force rage (e.g. 0 to 0.75 pounds) the sensor will provide a gradient response. Additional applied force above this force range (> 0.75 pounds) will not result in any additional sensor output.

Normal force sensors typically operate at sensitivity levels above the tactile ranges and provide a repeatable response relating the force applied perpendicular to the surface of the sensor. Many times the external force applied to the end-effector acts not only perpendicular to the sensor surface but parallel to it requiring detection of shear to totally resolve the external force. Coupled normal and shear forces can produce torques on the end-effector which can also be induce by a pure twisting action on the end-effector.

Sensors for each or a combination of these applications are available. A summary review of some of these sensor technologies is provided below

1. **Strain gage.** The strain gage force sensor operates on the principle of a change in resistance of a wire when it is stretched and its diameter thus reduced. Physically the strain gage consists of a flat pattern of wire which is bonded to the object to be measured. An applied force causes the object - and thus the gage - to distort and the resistance to change. Usually two or four gages are connected in a bridge pattern to help cancel the effects of changes in temperature and to multiply the output signals.

   A strain gage does not measure force directly, but measures the strain in a member caused by the applied force. A force sensor, or load cell, may be produced from strain gage(s) by bonding the gages to a member which will distort under applied force. By the sensitivity level of the gauge and the manner in which the gauge is attached to the strained member, in the tactile, normal force, and torque applications. A strain gauge appropriate for the tactile range is likely to have fatigue and failure problems when stressed at the higher force levels.

   Strain gages are a proven technology available from multiple sources. They have the drawback of producing a low level (millivolt) output signal, making them subject to noise interference. With proper shielding and electronics design this need not usually be a major problem.

   The major objection to the use of strain gages as a force sensor lies in the requirement for a distortable mechanical member to which to bond the gage. It may be difficult to

include a suitable member in the design of the end effector without compromising the gripping ability.

2. **Silicon strain gage.** A more recent, but still well developed, technology is the use of silicon strain gages. In these the strain gage is formed as part of a silicon integrated microcircuit. These are often combined on the chip with a diaphragm to form a pressure sensor or with a known miniature mass to form an accelerometer. However, custom devices may be manufactured which could measure applied force at one or more points. One company, IC Sensors, 1701 McCarthy Blvd., Milpitas, CA 95035 (408) 432-1800, manufactures a "Tactile sensor array" composed of such devices. The device is expensive, costing approximately $1000. Additional literature on the device and any similar structures has been requested.

3. **Piezoelectric.** Materials which exhibit the piezoelectric effect produce a voltage when an external force is applied. Most of the ceramic piezoelectric materials available do not have the sensitivity necessary to make a practical force sensor for this application. The fingertip sensor is an application of several piezoelectric strips. There is another class of materials called ferroelectrics which may be suitable for this application. Although no commercial force/tactile sensors using these materials are available, one of them - polyvinylidene fluoride (PVDF) has been used to fabricate such tactile sensors. This material has the advantage of being this (40 microns) and flexible and can thus be shaped to conform with non-flat surfaces.

4. **Piezoresistive.** Materials are available which exhibit a change in resistance with applied force. An example of this type is the plastic film sensors previously manufactured for ORBITEC. Although the response of these sensors may be non-linear, the sensitivity and range is compatible with this application. Non-linear response is not a major factor in a computer controlled system as long as it is repeatable.

5. **Conductive Membranes.** Sensors based on conductive elastomers have been developed by MIT and the Barry Wright Corporation among others. Elastomers vary their resistance with applied force, but only along one axis. Conduction does not take place along other axes. These can offer fine resolutions (on the order of 0.1 inch) spatially and adequate sensitivity to applied force. Electronic interfaces are more complex than other sensors, making them less than perfect for this application. They should certainly be considered for the more demanding multiple sensor requirements of future developments.

6. **Other general types.** There are several other types of force sensors which have been demonstrated in the laboratory. These include magnetoresistive, ultrasonic, and magnetoelastic based devices. While successful demonstrations have been made, commercial devices do not yet exist. Additionally, the interface and control electronics are complex. These may be ruled out for this application under the scope of this effort; however, the development of these technologies should be monitored for possible future use.

2.1.2.2 Tactile and Force Sensor Research & Development

The problem of providing adequate robot control and feedback of information to a computer or human operator is a difficult one. Even where the robotic manipulator system is limited to a six or seven degree-of-freedom arm with a one degree-of-freedom end-effector an appropriate sensor system to provide sufficient information to the controlling unit whether it be human or computer. Sensors are a key technology in the control of robotics. For telerobotics, the human interface is also extremely important such that all of the information collected by the sensor is communicated correctly to the human.

Sensory feedback control systems for robotics begin with the need for a quality sensing of the environment. Vision is probably the most important sensory feedback information with "man-in-the-loop" systems. Force/torque feedback information from the end-effector is a fundamental requirement. Conveyance of the sense of touch contact (tactility) with an object, and detection of slippage at the end-effector/object interface are also extremely valuable data for precise robotic controls. Tactility is also useful in identification of object, shape and orientation, and surface characteristics. This latter capability can be extremely important when vision is blocked, degraded or failed.

The ultimate approach would be to have a single sensor which would be applicable to tactile, normal force, shear force, and torque information. Because it is very difficult for a single sensor to be sensitive to forces in both the tactile range and higher force/torque, range, ORBITEC's approach is to divide the entire force regime into tactile and force ranges with appropriate sensors and stimulators. This approach reflects the design of the human hand where different sets of receptors exist for tactility and force/torque inputs. ORBITEC has conducted research and development in two major sensor approaches which tend to compliment one another; (1) a sensor that produces linear output in the tactile ranges, and (2) a fingertip sensor which can resolve forces into three orthogonal force and a torque along the principal axis. The latter is a development effort being internally funded by ORBITEC and the State of Wisconsin which began prior to this SBIR award but contributes greatly to a potential sensor interface.

From this effort, new applications of this sensor technology are being analyzed for an integrated normal and shear force sensor. These research and development efforts, summarized below, were conducted ORBITEC as internal research and development supported by the State of Wisconsin and are proprietary to ORBITEC.

Piezoresistive

ORBITEC personnel have developed flexible piezoresistive sensors which are extremely sensitive in the tactile range of touch. Figure 10 illustrates the sensor size and flexibility. The response of these sensors were tested via a controlled rate compressive test configuration are shown in Figure 11. The sensors consist of a molybdenum-impregnated vinyl which is layered against a silvered conductor. The sensitivity and hysteresis characteristics can be modified by the vinyl mix. By modifying both the composition and the configuration of the composite materials of the sensor, different force ranges and sensitivities have been demonstrated. Tests were paralleled between the ORBITEC sensor and the Interlink (Maralat) piezoresistive sensor with the ORBITEC sensor being more sensitive in the tactile range but with much lower saturation force levels.

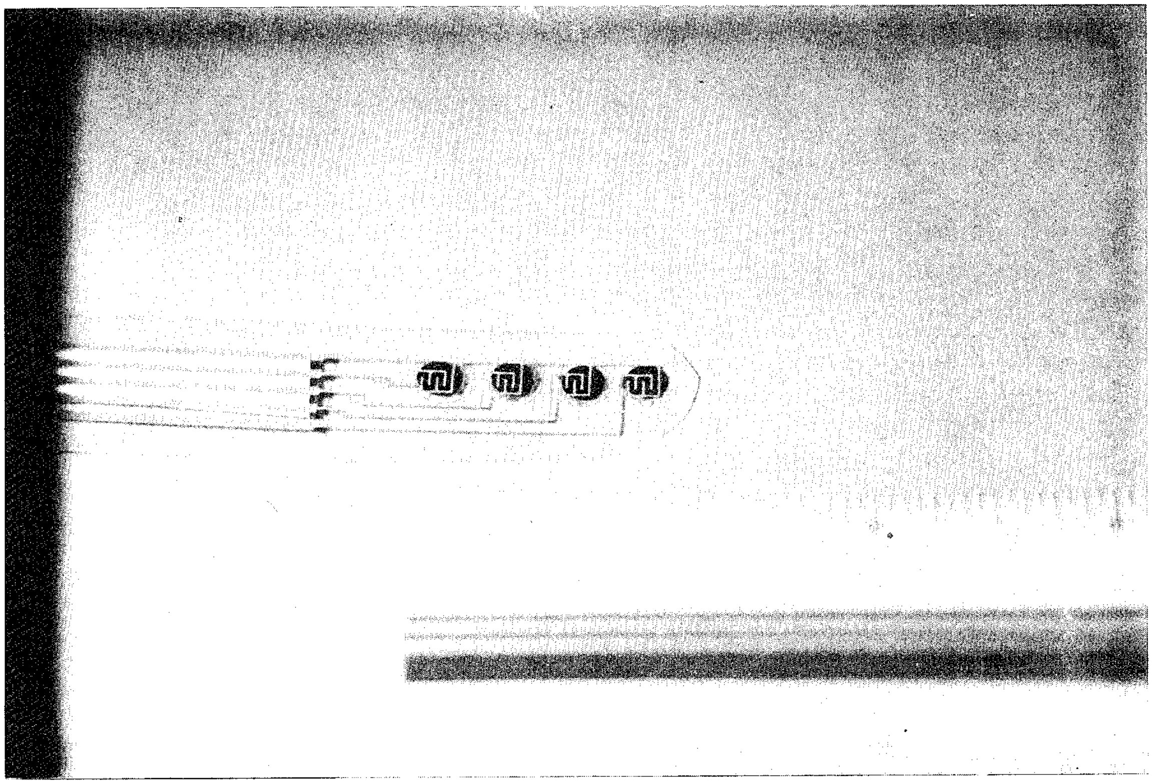


Figure 10a. Piezoelectric Sensor Prototype Configuration

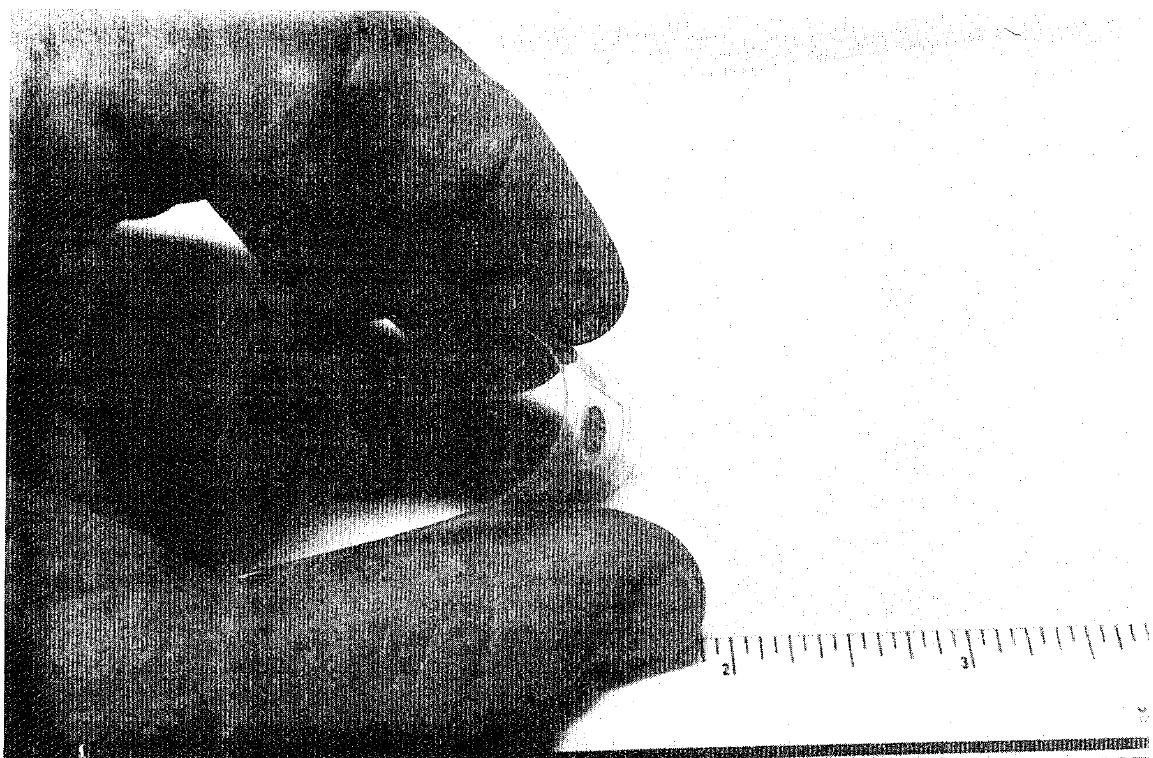
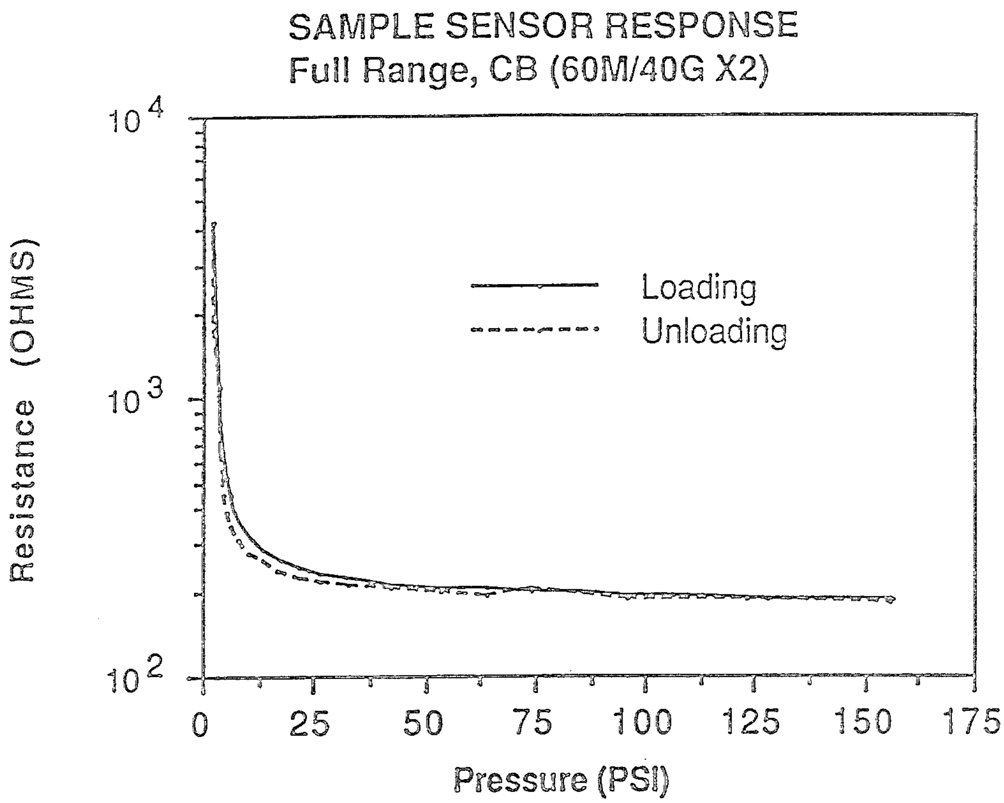


Figure 10b. Demonstration of Piezoelectric Sensor Prototype Flexibility for Curved Surface Application



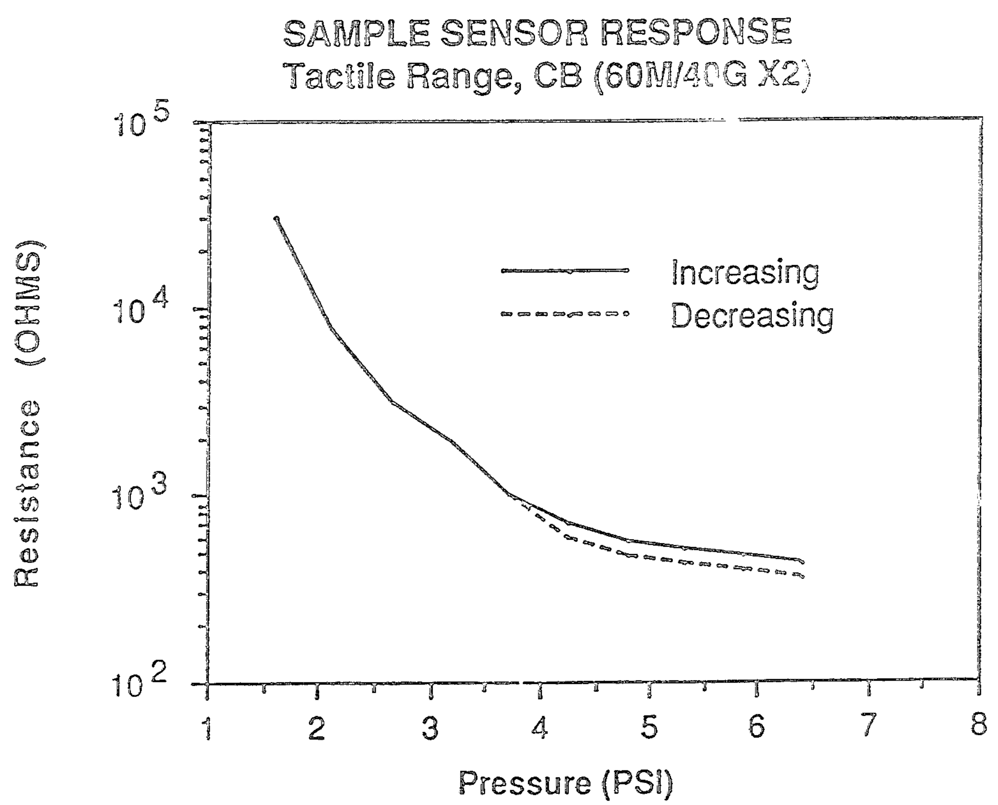


Figure 11. Compression Test Results of the Piezoelectric Prototype Sensor Response

This sensor appears to have good potential with the following recommended modifications:

- a more flexible substrate rigidized around the element
- modified conductive mixture for less hysteresis
- more consistent mounting technique

These sensors should be pursued upon definition of the test slave device such that a specific design of the substrate and size of the sensing elements may be accomplished. No further effort is recommended until the slave application is defined.

Multiple-degree Robotic End-Effector Sensors (MRES)

Robotic devices have proven their worth many times particularly in the manufacturing industries and telerobotics in the nuclear and subsea industries. However, growth in the application and capability of the devices has been constrained by limitations in sensing, reacting, and controlling the end-effector's interface with the work environment. Devices in use today typically rely on sensors only able to resolve force in a single direction. As the requirements and capabilities of the end-effectors increases, so does the requirement of monitoring forces, tactility. shears, and torques to provide adequate control.

Most tactile sensors today are one-dimensional pressure sensitive arrays using many different sensing elements. The sensing elements may include conductive rubber, piezoelectric or piezoresistive elements, optical methods using the indices of refraction, electro-optical transduction, and fiber optics. Each has advantages and disadvantages but most are restricted to force detection in one plane, normally the normal plane. Detection of shear and torsional forces are difficult with the state-of-the-art technologies on the market.

Multiple-degree Robotic End-effector Sensors (MRES) are proposed as compliant members containing several transducer elements attached to 1) the tips of a robot dexterous end-effector that would resolve three orthogonal forces and a torque, and 2) along the sides of the end-effector to resolve normal and shear components along a surface. The MRES functions to detect contact, applied force, curvature, slippage, and the center of gravity of a grasped object. Several fingers operating together on a dexterous end-effector would be extremely valuable to increase the capability of the robotic or telerobotic system to detect its status and configuration. The sensing capability of the robot hand would be similar to the sensing ability of human fingers measuring forces on the order of 0.1 gram are anticipated possibilities with high incremental resolution. Independent force, tactile, and torque sensors could be eliminated. Servicing of remote hardware will be augmented by the ability of these sensors to detect forces

similar to the major sensing functions of human skin leading to higher performance and increased servicing capability.

A four-degree-of-freedom (DOF), tactile fingertip sensor, originally developed for manufacturing applications, and a two-DOF skin-layer sensor is proposed for use in teleoperated and automated robotics systems. Both sensor configurations will monitor multiple planes of forces over a wide force range. The fingertip configuration has potential to resolve forces into three orthogonal planes and a torque.

The skin-layer sensor has the potential of resolving the normal, shear forces and possibly torque. This effort will extend research and development activities into the application of robotic manipulators and dexterous end-effectors for servicing tasks. Integration of these end-effector sensors will allow sensitive force feedback from the slave robot. Other features of the MRES include:

- can be optimized with respect to its shape, its sensing element size, and location to give favorable signal characteristics,
- is linear over a wide range of applied forces,
- has low hysteresis and good repeatability,
- can be linearly decoupled to allow measurement of multiple degrees-of-freedom appropriate for grippers,
  - Fingertip configuration - two tangential forces, normal force, and torque about the normal axis),
  - Skin-layer configuration - normal force, shear force and possible torque about the normal axis),
- is inert to most environmental influences,
- can be easily constructed with minimal material costs, and
- can be made rugged, yet possesses sufficient compliance for practical force control,
- is lightweight and inexpensive to manufacture.

Preliminary research efforts were concentrated on a single, thumb-sized sensor to demonstrate the approach feasibility. A three-dimensional sensor tip in accordance with the preliminary configuration, is capable resolving forces in three orthogonal directions and of providing signals indicative of the force and/or torque components acting upon the sensor tip at the point of

contact. The sensor tip has an elastomeric body shaped to have a circular base and a convex surface extending therefrom. Four transducers that convert strain in the body to output voltage are place about the convex surface and provide electrical output signals which may be combined to produce signals corresponding to the force components acting at the point of contact.

In the initial configuration, the elastomeric body of the sensor tip was sized slightly larger than the adult male thumb, and was composed of silicone rubber, which is chemically inert and approximately as compliant as human flesh. Though easily deformable, the material displays low hysteresis and good repeatability. Its compliance is preferably greater than that of the objects which will be grasped, so that substantially all advancement of the sensor tip toward the object after initial contact occurs because of compression of the sensor tip rather than the object. Because the stress-strain relationship of the sensor material is known (whereas that of the object may not be known) the actual amount of force (or pressure) exerted by the sensor on the object can be determined. As shown in Figure 12 and 13, the sensor tip is preferably in the shape of one-half of an ellipsoid taken along its major axis, the ratio of the major axis to minor axis being preferably about 1.6 for optimal signal amplitudes. New configurations and sensor concepts utilizing this approach will be further described later in this proposal.

The preliminary fingertip configuration maintains four transducers positioned in selected positions and orientations about the convex surface of the sensor tip and are preferably composed of a piezoelectric polymer film having lead wires attached. Wires carry the signals of electrical voltage that correspond to the deformation, or strain, experienced by the elastomeric body. The signals are amplified by a signal amplifier, and then are provided to a hard wired processing circuit or a computer which decouples the electrical signals into the individual force components (see Figure 14). The decoupling is readily accomplished in that the interactions between the transducers are well understood and lend themselves to decoupled calibration means.

The sensor tip can form part of a finger in a robotic hand for grasping objects and may be modified into a two-dimensional skin-layer sensor configuration. When there are three or more fingers in a robotic hand, the sensor tip may emulate the human hand by determining the forces exerted upon the robotic hand by the objects being manipulated. Incorporation of a three-fingered robotic hand, each finger of which can determine multiple force components, enables the robot to form a three-point three-dimensional grasp that provides a better, more stable grip than conventional two point grips. The sensor tip of the present invention provides feedback information that allows the robot to sense when the object has been contacted, when it is slipping from the hand, or when the object has been picked up away from the

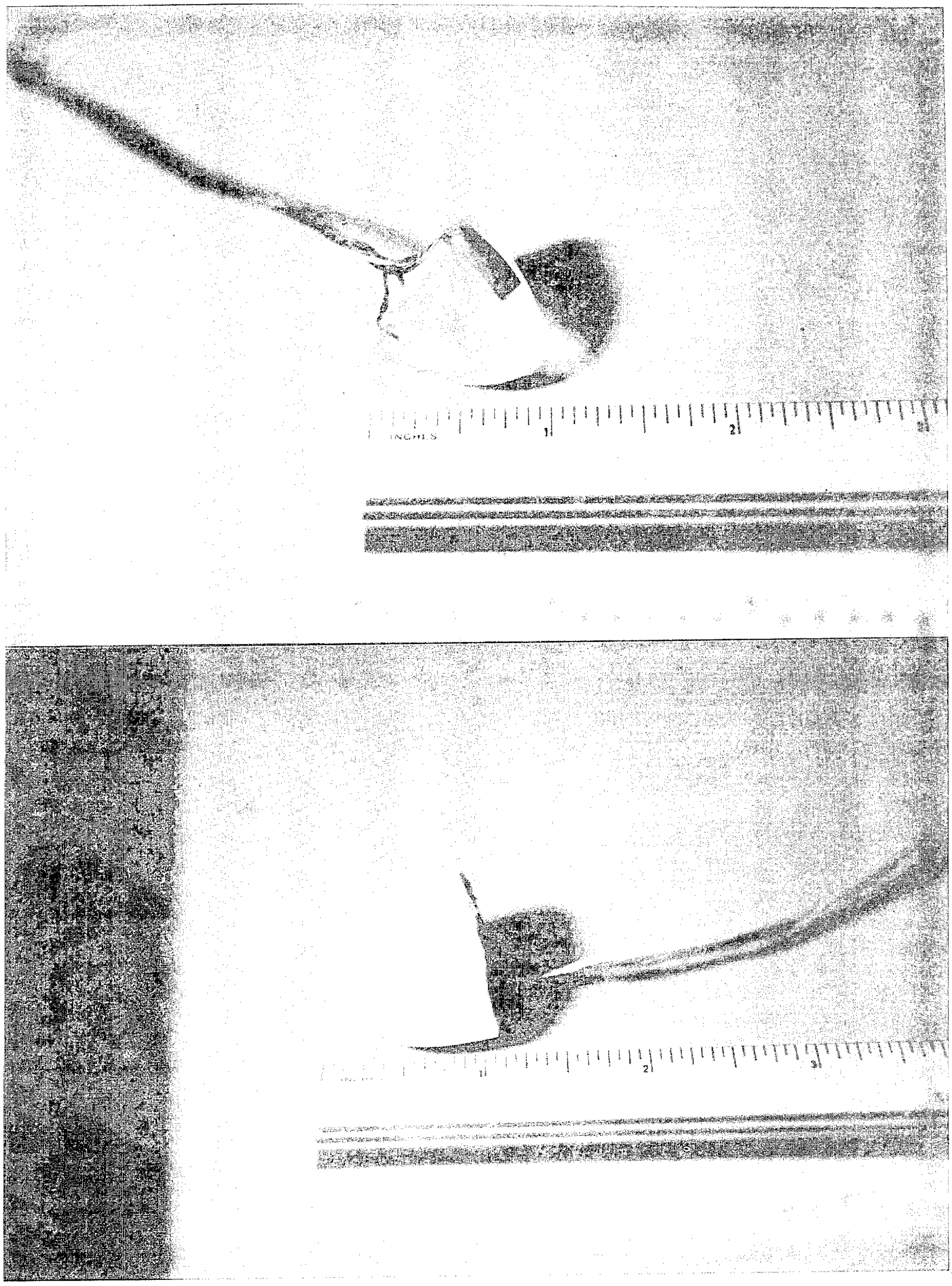


Figure 12 Prototype MRES Fingertip Sensors

center of gravity, as well as allowing the amount of force exerted on the object by the sensor tips to be monitored. The two-dimensional skin-layer configuration would monitor shear and normal forces to relay slip and other torque related data to controllers.

The sensor tip can be easily constructed with minimal material, manufacturing and calibration costs, yet can be rugged and remain accurate over a large range of applied forces. Similar to the tactile sense of human fingertips, the incremental resolution is high without the need for high absolute accuracy. Absolute positioning of the transducers on the tip body is not critical, as a decoupling calibration is easily performed.

Each different component of the force applied to the sensor, whether it is normal, tangential, or torque, produces a unique signal. Therefore, after the signals have been amplified, the signals must be sent to a computer for decoupling which will resolve the applied force into its independent components. Table 3 provides summary of the fingertip elements characteristics based on currently available information.

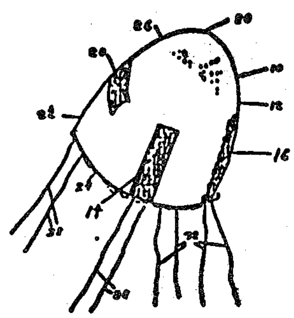


Figure 13. Overall Configuration of the MRES Element

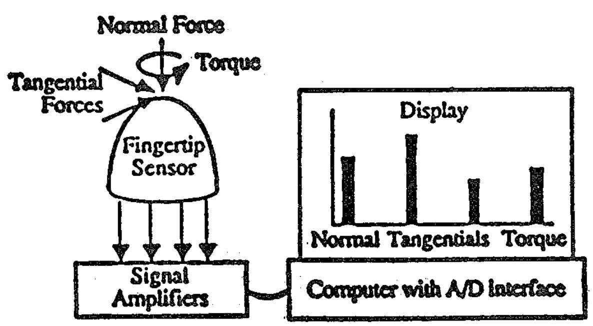


Figure 14. Fingertip Sensor and Signal Processing System.

Table 3. Characteristics of the Original Fingertip Approach

Linearity	1% Error at 4 Pounds of Normal Force
Hysteresis	3% Error at 7 Pounds of Normal Force
Repeatability	<1% Error at 5 Pounds of Normal Force
Range	0.5 Ounces to 15 Pounds

2.1.2.3 Tactile and Force Sensor Comparisons and Evaluations

Each of the sensor technology areas were reviewed and specific sensors were assessed where ample data and experience was available. Comparisons are provided in Table 4. ORBITEC recommends continued development of the fingertip and layered skin configurations of the Multi-degree-of-freedom Robotic End-effector Sensors for detection of tactile, normal force, and shear force information. The piezoresistive type sensors may be continued in parallel as a complimentary or substitute sensor in the tactile range.

2.1.3 Position Control

To provide position control information from the master controller glove to the system, it is necessary to measure the finger angles of the master. On a full hand controller glove, this could involve 14 knuckle position measurements and 6 finger and thumb side angle measurements. All of the sensors to accomplish these measurements must be integrated into a mechanical structure that comfortably attaches to the hand and fingers, and reliably and accurately tracks finger movements. Thus, any possible sensor and mechanical elements must be physically small so as not to interfere with hand movement. Additionally small size and low mass are required to minimize operator fatigue. Actual physical attachments must be minimized, again to reduce fatigue and interference with hand motions. Ideally the device should be of such a size and weight as not to impede any normal finger movements of the operator.

Telerobotic devices are inherently more dependent on relative data than on absolute data unlike automated industrial robotic applications. This is largely due to the adaptive capability of the human operator to environmental circumstances. For exemple, at any point in time, you can tell someone to a large accuracy, the angle of a specific finger joint angle; but you can adaptively grasp and manipulate quite well as long as you are provided enough

Table 4. Preliminary Comparison of Tactile and Force Sensor Technologies

GENERAL SENSOR TECHNOLOGY	APPLICABILITY TACTILE	NORMAL	SHEAR	TORQUE	ACCURACY	REPEATABILITY	STABILI
STRAIN GAUGE	GOOD IF NOT ALSOFOR LARGE FORCES	GOOD IF NOT ALSO FOR TACTILE REGION	NO	ONLY IN COUPLES	EXCELLENT	EXCELLENT	GOOD
PIEZOELECTRIC			DEPENDENT ON CONFIGURATION		GOOD	GOOD	GOOD ONLY FORCES
PIEZORESISTIVE			NO	ONLY IN COUPLES	GOOD	GOOD	GOOD, TEM SENSITIVE
CONDUCTIVE FILMS			NO	ONLY IN COUPLES	GOOD	GOOD AFTER BREAK-IN LOAD CYCLES	SOME CREE TEMPERATU
MAGNETORESISTIVE			NO	ONLY IN COUPLES	GOOD	GOOD	GOOD, TEMP SENSITIVE,
MAGNETOELASTIC	FAIR, CONFIG DEPENDENT	GOOD	DEPENDENT ON CONFIGURATION		GOOD	GOOD	BETTER FOR FORCES, SO

R&D EVALUATIONS	APPLICABILITY TACTILE	NORMAL	SHEAR	TORQUE	ACCURACY	REPEATABILITY	STABILITY
FINGERTIP	GOOD	GOOD	IN 2-D CONFIG	ALONG BODY AXIS	GOOD	GOOD	GOOD ONLY F FORCES
PIEZORESISTIVE	GOOD	SATURATES EARLY	NO	NO	GOOD	GOOD AFTER BREAK-IN CYCLING	GOOD
INTERLINK / MARALAT	POOR	GOOD	NO	NO	GOOD	GOOD AFTER BREAD-IN CYCLING	HIGH FREQUE OUTPUT DUR COMPRESSIO
LORD CORPORATION	FAIR	GOOD	NO	NO	GOOD	GOOD	EXCELLENT

STABILITY	DURABILITY	COMPLEXITY	HYSTERESIS	SIZE
GOOD	GOOD IF NOT OVER STRESSED	SIMPLE	SMALL	↑
GOOD ONLY FOR DYNAMIC FORCES	GOOD	COMPLICATED SIGNAL AMPLIFICATION	SLIGHT HYSTERESIS DEPENDENT THE MOUNTING CHARACTERISTICS	
GOOD, TEMPERATURE SENSITIVE	GOOD	EXTREMELY SIMPLE	SLIGHT HYSTERESIS DEPENDENT ON THE PIEZO MATERIAL MIXTURE	
SOME CREEP EXPERIENCED TEMPERATURE SENSITIVE	GOOD	EXTREMELY SIMPLE	SLIGHT HYSTERESIS DEPENDENT ON THE FILM MATERIAL MIXTURE	DEPENDS ON CONFIG.
GOOD, TEMPERATURE SENSITIVE, SOME AGING	GOOD	MODERATE	SLIGHT HYSTERESIS DEPENDENT ON THE MATERIAL	
BETTER FOR DYNAMIC FORCES, SOME AGING	GOOD	COMPLICATED SIGNAL AMPLIFICATION	SLIGHT HYSTERESIS DEPENDENT THE MOUNTING CHARACTERISTICS	↓

STABILITY	DURABILITY	COMPLEXITY	HYSTERESIS	SIZE
OOD ONLY FOR DYNAMIC ORCES	EXCELLENT	COMPLEX SIGNAL AMPLIFIER	SLIGHT	THUMB-SIZE
OOD	GOOD	EXTREMELY SIMPLE, ARRAYS BECOME MORE COMPLEX	SLIGHT DEPENDENT ON THE VINYL MIXTURE CONTENT	VERY SMALL THIN
GH FREQUENCY NOISE JTPUT DURING OMPRESSION TESTS	GOOD	EXTREMELY SIMPLE, ARRAYS BECOME MORE COMPLEX	SLIGHT	SMALL THIN
CELLENT	EXCELLENT	MODERATE	VERY SLIGHT	LARGE ARRAY

2 of 2

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feedback on the operation environment. In the telerobotic system, the position sensor must demonstrate extremely high repeatability accuracy; however, extreme absolute accuracy is not required. This is true because: (1) there is no benefit to providing accuracy (in the master) that is significantly greater than that which a human operator can productively use; and (2) the angular position of the slave may not in an absolute sense equal the absolute position of the master.

Tactile and force information, as well as visual information, is returned to the operator who then alters the position of the master glove accordingly. The operator thus positions the master based on information other than the actual Cartesian position. A position accuracy on the order of +/- 0.5 to 3 degrees should be sufficient.

Of more importance are other sensor characteristics. The sensor must have a relative long life time. For example, many trim pots are limited to a life of 200 cycles. A lifetime of greater than 500,000 cycles should be considered. As previously stated, of major importance is the size, mass, and activation force of any potential sensor.

Several position control exoskeleton devices have been designed and constructed through WCSAR (see Figure 1 and Table 1 shown in Section 1.0 [Teeter, et al., 1988]). The A.D. Little/Exos master controller (Figure 15) is another valid point design from which to expand using hall effect sensors. Also, the Data Glove (Figure 16) developed in conjunction with the Nasa Ames Research Center is another point design to consider using light pipes, however, position accuracy has not yet been demonstrated for this system. ORBITEC used these existing prototypes and commercial devices as a point of departure for the OTCG.

2.1.3.1 Position monitoring options

There are a number of options for position sensors and for the means of integrating those sensors into the glove or an exoskeleton device. These options are identified and defined below.

2.1.3.1.1 Available sensors

An examination of the types of angular position sensors available today commercially reveals the following categories.

1. Potentiometers. A variable resistance potentiometer may be used with an excitation voltage to provide a variable voltaic output with shaft angle. The majority of potentiometers provide a variable resistance over ranges of 270 to 330 degrees of rotation. The actual values of resistance and taper (linear, logarithmic, etc.) vary but cover an extremely wide selection. The more common of small

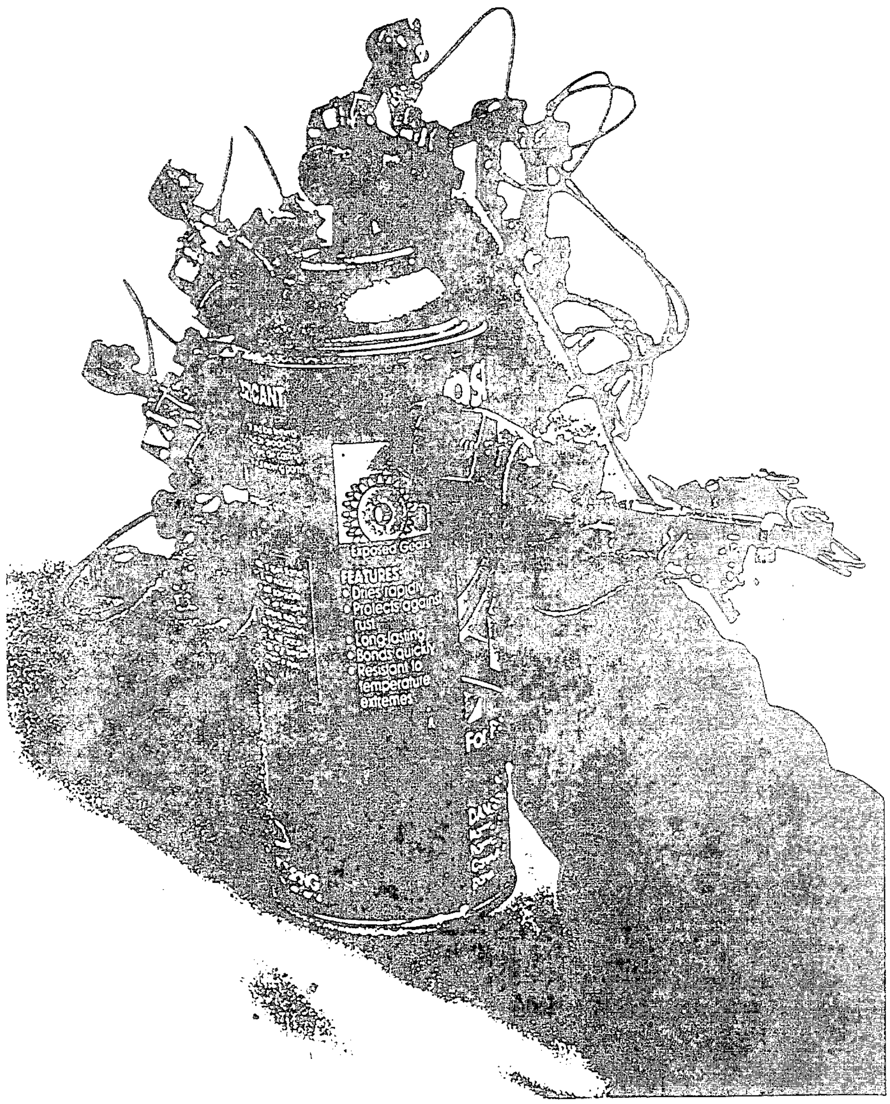

Figure 15. Series 2 Dexterous Hand Master by EXOS

United States Patent [19]

Zimmerman

[11] Patent Number: 4,542,291

[45] Date of Patent: Sep. 17, 1985

[54] OPTICAL FLEX SENSOR

[75] Inventor: Thomas G. Zimmerman, Flushing, N.Y.

[73] Assignee: VPL Research Inc., Palo Alto, Calif.

[21] Appl. No.: 428,322

[22] Filed: Sep. 29, 1982

[51] Int. Cl.[4] G01B 5/34

[52] U.S. Cl. .... 250/231 R; 250/551; 340/365 R

[58] Field of Search .... 73/760, 761, 763, 768, 73/774, 775, 800 340/365 R; 250/231 R, 551

[56] References Cited

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Primary Examiner—David C. Nelms
Assistant Examiner—J. Gatto
Attorney, Agent, or Firm—Richard L. Miller

[57] ABSTRACT

An optical flex sensor is provided and consists of a flexible tube having two ends, a reflective interior wall within the flexible tube and a light source placed within one end of the flexible tube and a photosensitive detector placed within the other end of the flexible tube to detect a combination of direct light rays and reflected rays when the flexible tube is bent.

11 Claims, 7 Drawing Figures

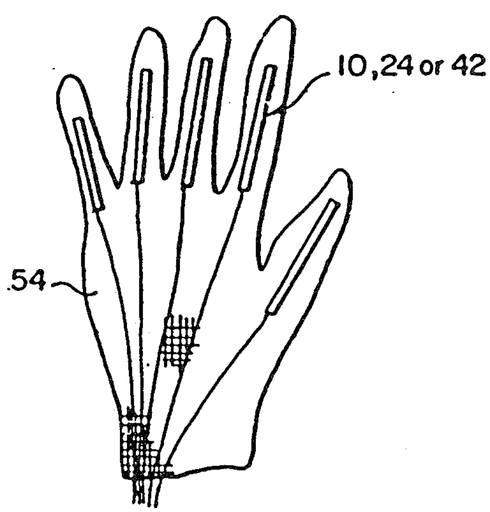

Figure 16. Patent Cover Sheet for the VPL Data Glove

potentiometers (trim pots and miniature controls) have shafts ending in screw slots making connection somewhat difficult. Furthermore, the activation forces required are greater than desired. The major draw back, however, of the common miniature potentiometers is their limited lifetime. Many are specified for a maximum of only 200 cycles.

There are potentiometers made primarily for position sensing in control systems. These have lifetimes of 1 to 20 million cycles. All offer adequate rotational ranges and are available in reasonable resistance ranges and linear tapers. Because they are designed for use in control systems, the necessary operating force is very low. The primary drawback to this type of potentiometer is its size. The smallest of the available control system potentiometers is approximately 0.5 inch diameter. If it were attempted to place 20 of these sensors, along with necessary mounting and connecting hardware, on a master control glove, the result would be unwieldy. The total mass would be great enough to cause operator fatigue with prolonged use.

2. Optical encoders. Optical encoders provide high accuracy and fine resolution of angular position measurement. They operate on the principle of either a light shining through a precision encoded mask giving an absolute position in binary (absolute position type) or a light shining through a precision ruled uniform pattern giving a count for each fixed angle of rotation (relative position type). In the latter case, it is necessary for the sensor signal conditioner to keep count of the number of pattern marks which have been passed since a known origin to determine absolute accuracy.

Optical encoders are available in accuracies ranging from 15 pulses per revolution to 2000 pulses per revolution. They are available from a variety of sources as off the shelf items. They are, however, larger than desired. The smallest of the relative position types are 0.5-0.75 inch diameter and offer resolutions of only 15 to 200 pulses per revolution. Besides the low accuracy, the relative position type encoders require complicated signal conditioning and indexing to provide an absolute position indication. More accurate encoders and absolute position encoders are much larger - on the order of 2-3 inches diameter. Additionally optical encoders are expensive.

3. Magnetic encoders. Magnetic position encoders are of two types: variable reluctance and Hall effect.

Variable reluctance types are usually of limited accuracy, providing only a few pulses per revolution. They suffer the same drawbacks of signal conditioning requirements

as the relative position type of optical encoders in that an absolute index and pulse counting is required to determine absolute position. They are primarily used in low accuracy systems such as the spark timing of automobile engines.

Hall effect devices operate on the principle of Hall voltage production in crystals. Certain crystals develop a potential voltage when placed in a magnetic field. The magnitude of this Hall effect voltage is dependant upon the magnitude of the field. In a Hall effect angular position sensor, a Hall sensitive crystal is placed near a permanent magnet. As the sensor is rotated, the crystal orientation and proximity to the magnetic field changes producing a variable output voltage. The primary drawback of Hall effect sensors is their size. The smallest devices are on the order of 0.6 to 0.75 inch diameter.

4. Light pipe encoder. The light pipe encoder, as used in the VPL glove, consists of a hollow tube with a partially reflective interior. A light source (LED) is located at one end and a light sensor (Photo diode) is located at the other. When the tube is straight, light from the source strikes the sensor directly since it is in direct line of sight. As the tube is bent, less light can follow a direct path from source to sensor and a larger portion is transmitted by reflection from the interior tube walls. By measuring the amount of received light at the sensor it is possible to determine the angle at which the tube is bent.

The accuracy of this sensor is limited. Also, there is a problem in repeatability in that the tube tends to slip with motion of the hand and fingers.

5. Synchro resolver. The synchro resolver position sensor uses a multiphase motor and sine wave excitation voltage to produce a sinusoid output signal. As the armature of the motor is rotated the phase relationship of the output signal will vary. The phase of this signal may be used to determine the angular position of the encoding device. Synchros are well proven reliable technology. Decoding is not extremely complex and accuracy is easily sufficient. However, synchros are too large (on the order of 1.5-3 inches diameter) to be useful in this application.

6. LVDT. The linear variable differential transformer (LVDT) is actually a linear position indicator instead of angular. It could, however, be used to measure finger position by mounting on top of the finger and attaching it with flexible joints. The LVDT consists of a movable solid core of ferrous material sliding in a tube with a double transformer winding. An excitation signal is applied to one winding. As the core moves the signal produced as an output at the other winding

will vary with the core position. The LVDT is a well proven available technology requiring relatively simple signal conditioning. They are inexpensive and available off the shelf. Sizes range upwards from approximately 0.2-0.25 inch diameter by 1-2 inches long. As with potentiometers, the use of 20 LVDTs on a full scale master control glove would be prohibitive.

2.1.3.1.2 Possible new sensors

ORBITEC examined the available sensor options described above and concluded that none of them completely satisfied the requirements of the OTCG. As a result, a separate research and development program was initiated using ORBITEC funds supplied by the state of Wisconsin Department of Development. Two new concepts for position sensing were developed and explored. One was a new optical rotational sensor. The other was a unique ultrasonic ranging system. A third sensor type identified needing development was identified (a small sliding flexible optical position sensor), but was not pursued because the system that required it was not ranked highly. The other two concepts are briefly described below.

1. Small optical rotational sensor. This sensor would use a light source (LED) and a light sensor such as a photodiode. The source and sensor would be separated by two pieces of polaroid plastic with the transmission planes aligned when the light sensor is in the zero angle position. As the two halves of the sensor are rotated through 90 degrees, the light transmission decreases to zero (see Figure 17).

   Such a sensor has the potential to be manufactured in an extremely small package - on the order of 0.15 to 0.2 inch diameter. It would require fairly simple signal conditioning and provide sufficient resolution for the desired purpose. This offers a high potential return in the form of a simple, low cost, physically small position sensor.

2. Ultrasonic finger positioning system. A possible position measuring system may be designed using ultrasonic measurement techniques. Such a system would measure the position of the fingertips of the master glove directly rather than measuring the joint angles and calculating the resulting positions. This would allow the glove to be unencumbered by any complex exoskeleton, be free to move with no attachments, and be light in weight.

Additional information and research results on these concepts is presented in Section 2.1.3.2.

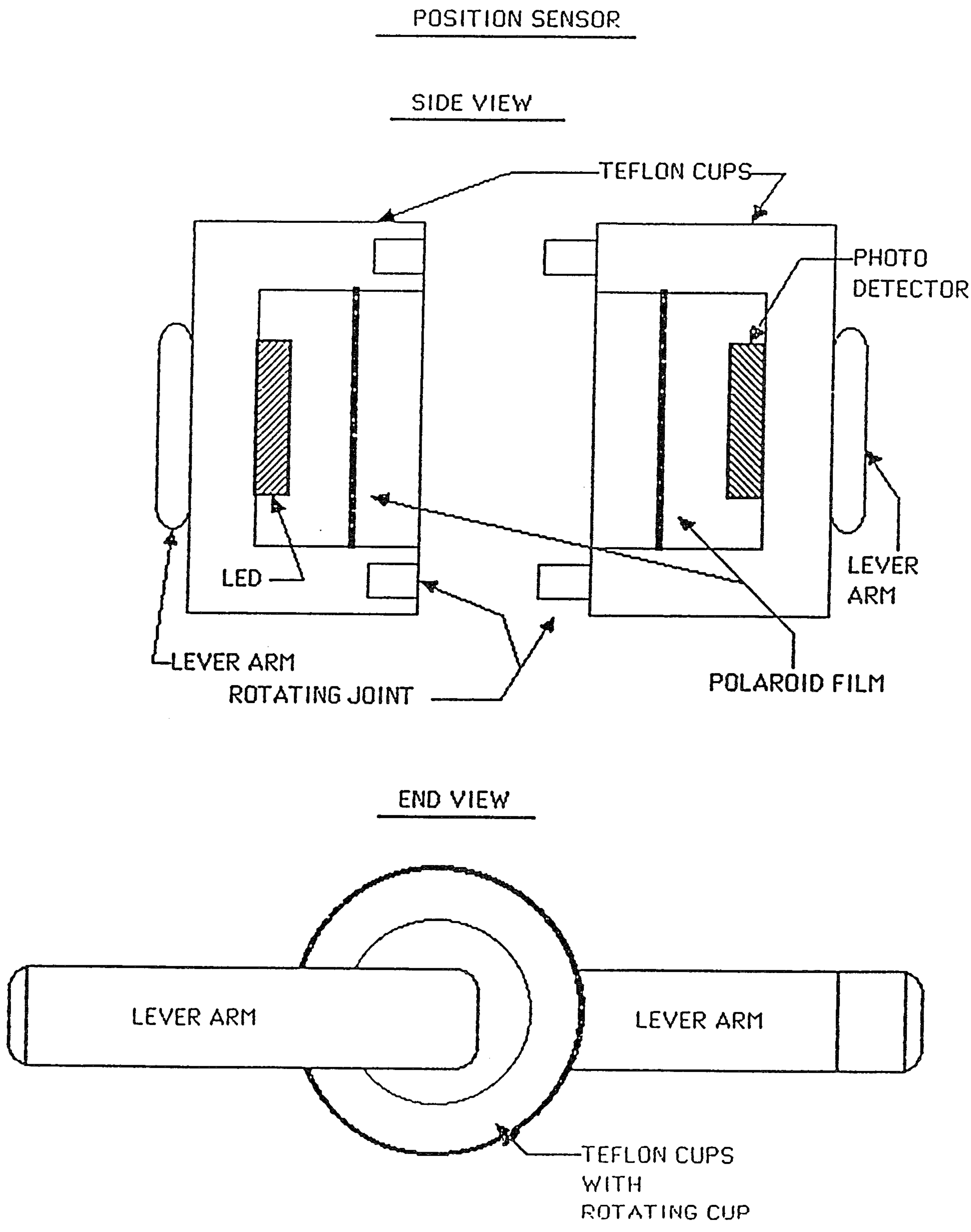

Figure 17. Schematic of the ORBITEC Rotation Sensor

2.1.3.1.3 Sensor integration options

Assuming an adequate sensor is available, the problem that remains is to integrate that sensor into a device that: (1) comfortably attaches to the operator's hand and fingers; and (2) reliably and accurately tracks finger movements. The entire device must then readily integrate with available arm master controllers. A number of solutions to this problem were investigated. Preliminary concept development meetings of the research team led to the following conclusions and results:

(1) Although there was a strong desire among research team members to develop a concept which emphasized small mechanical elements, integrated into a glove, <u>along the sides</u> of the fingers, no practical way of implementing this approach was found

(2) With one notable exception, all of the potentially practical solutions involved mechanical elements located on the back and/or above the back of the hand and fingers.

(3) The entire position and configuration of a finger in a three-axis coordinate system can be determined from knowledge of the location and orientation of the distal finger link.

(4) The OTCG must be readily integrable and compatible with appropriate arm/wrist master controllers that are force reflecting.

Six concepts were identified as possible design options for the controller device. Five of these concepts are shown in Figures 18 to Figure 23. Each drawing shows a device concept as it would integrate with an average (50th percentile) male human hand. Four of the concepts are intended to be integrated into the fabric glove worn by the operator which would also contain the tactile stimulator array. The fifth is a separate exoskeleton that would be part of a hand bracket that would integrate directly with an arm/wrist master controller. The sixth concept is very different from the others and will be discussed separately.

Figure 18 shows a "Flexible Linkage" concept in which the ends of a flexible link are attached to the glove and hand on either side of each finger knuckle. On one end of each link is a rotational position sensor that measures the angle of closure of that joint.

Figures 2.1.3-6 and 2.1.3-7 show a "Roller" concept. In this concept a series of three rollers is mounted over each finger knuckle. A rotational position sensor is integrated into each of the rollers. A tendon is wrapped sequentially around each of the

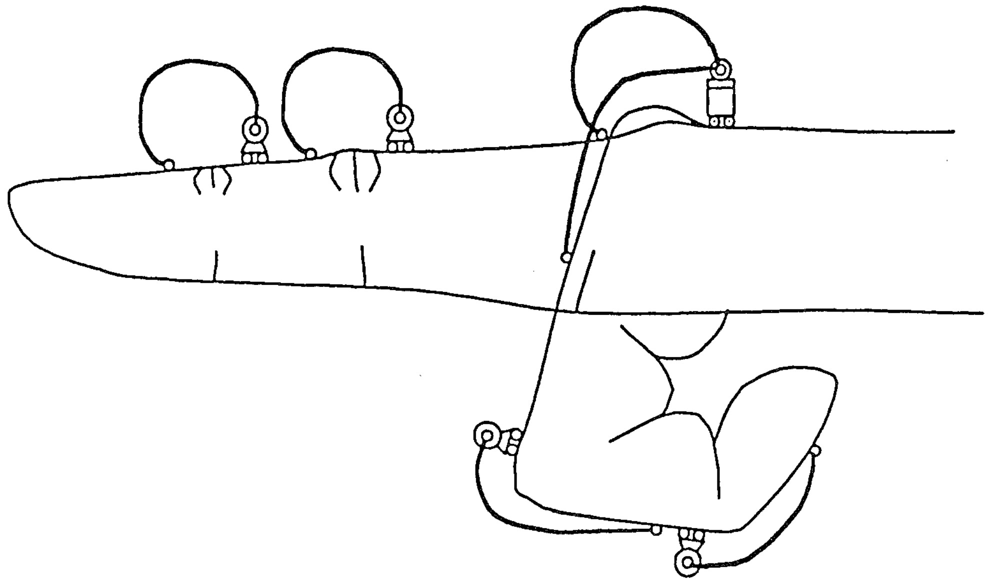

Figure 18. Flexible Linkage Position Monitoring Concept

three rollers and then lightly tensioned and anchored on the back of the hand. The angle of closure of a joint is measured as the sum of the angles of the three rollers/sensors mounted on that joint. This concept allows closer integration of the system into the glove. It also facilitates use of ORBITEC,s new position sensor concept in that rotation of each of the sensors can be kept below 90 degrees within limits of the sensor. Table 5 shows the results of a preliminary analysis of the distance of travel for each of the tendons during finger closure. The distance of travel of the distal tendon is 2.2 inches.

The light spring tension in the tendon may (if properly implemented) have an advantageous side effect. It may reduce operator fatigue in operations that require the operator to hold the hand in a fixed position for an extended period of time. It is known, for example, that it is easier to lightly grip an object, say a coffee cup, for a period of time than to hold the fingers in that same position without gripping the cup. It may be possible to use the spring tension to simulate the more restful light-grip condition.

Figure 21 shows a "Cable/Sheathing" concept. In this concept a sliding flexible optical position sensor positioned over each finger knuckle measures the angle of closure of that joint.

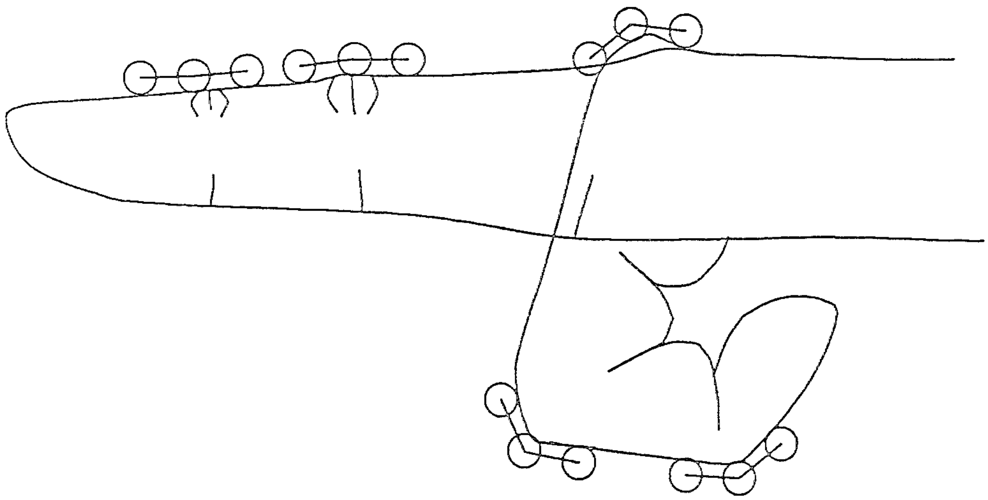

Figure 19. Roller Posisition Monitoring Concept - Side View

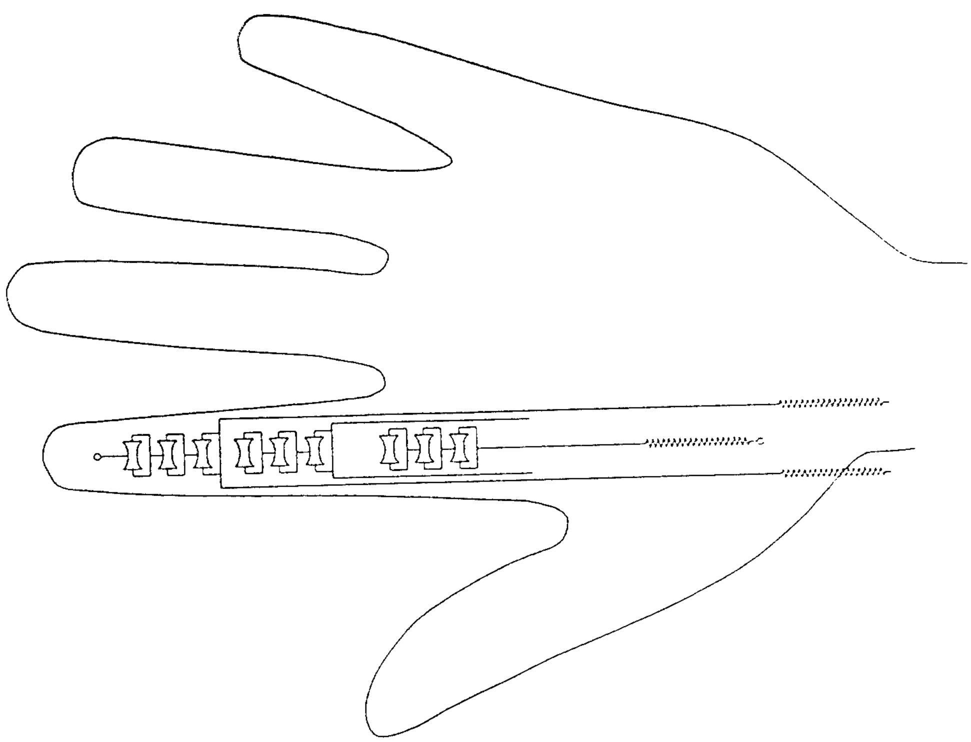

Figure 20. Roller Position Monitoring Concept - Top View

Table 5. Rotational and Distance Specifications for Roller Position Monitoring Concept for 50% Male

	Angle of Rotation	Radius	Travel: inches Distal	Medial	Proximal Pitch	Total	Spring Force
Distal	90°	0.344	0.540	0.737	0.933	2.210	TBD
Medial	90°	0.469		0.737	0.933	1.670	TBD
Proximal Pitch	90°	0.594			0.933	0.933	TBD

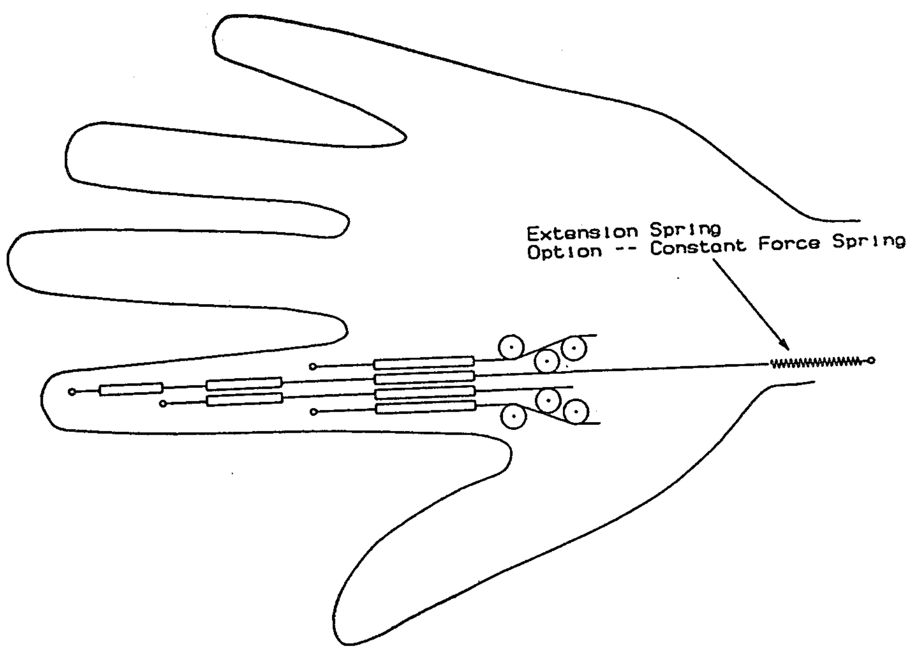

Figure 21. Cable/Sheathing Position Monitoring Concept

The sensor sliding element is driven by a cable in a sheath, analogous, for example, to cables used to operate bicycle hand brakes and shifting mechanisms. Optionally a light tension spring could be added to the cable to potentially reduce operator fatigue as described in the roller concept above. Table 6 shows the results of a preliminary analysis of the distance of travel for each of the cables during finger closure. The distance of travel of the distal tendon is 1.9 inches.

Table 6. Rotational and Distance Specifications for Cable/Sheath Position Monitoring Concept for 50% Male

Specification for Cable/Sheating Concept ~ 50 % male

	Angle of Rotation	Radius	Travel: Distal	Medial	Proximal Pitch	Proximal Yaw	Total	# of Turns Pulley	Spring Force
Distal	90°	0.25	0.393	0.589	0.785	0.161	1.928	2.455	TBD
Medial	90°	0.375		0.589	0.785	0.161	1.535	1.954	TBD
Proximal Pitch	90°	0.500			0.785	0.161	0.946	1.204	TBD
Proximal Yaw	+/-20°	0.23				0.161	0.161		TBD

Figure 22 shows a modified version of the A.D. Little/Exos concept. The drawing shows the effect on the concept of using a much smaller rotational sensor. This reduction in size may enable integration of the device into a glove.

Figure 23 shows the "Mechanical Linkage" concept. This concept is fundamentally different from the previous four concepts. It is a separate exoskeleton that would be part of a hand bracket that would integrate directly with an arm/wrist master controller. The tactile stimulators would still be installed in a glove worn by the operator. The exoskeleton would be mounted over the glove.

This concept measures the distance and orientation of the distal finger link with respect to a bracket mounted on the hand. This information is all that is needed to uniquely determine a finger configuration and all joint angles for the slave. The recognition of this fact is a key finding of this project. Demonstration of this fact and derivation of the required coordinate transformations to determine all joint angles are given

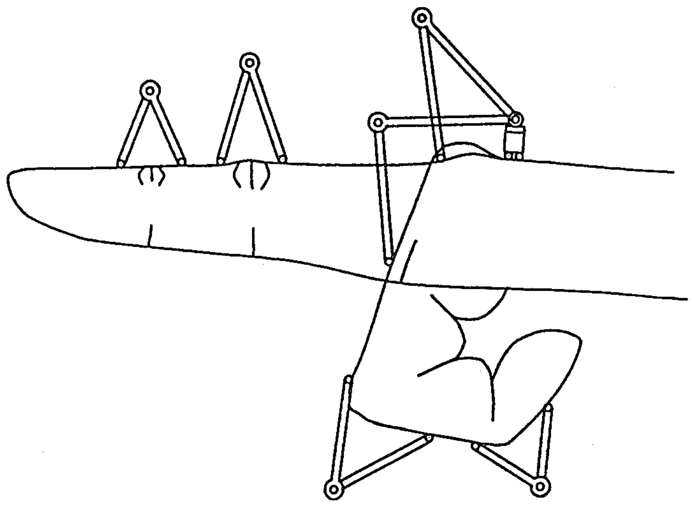

Figure 22. Application of the A.D. Little / EXOS Approach to the Glove Configuration

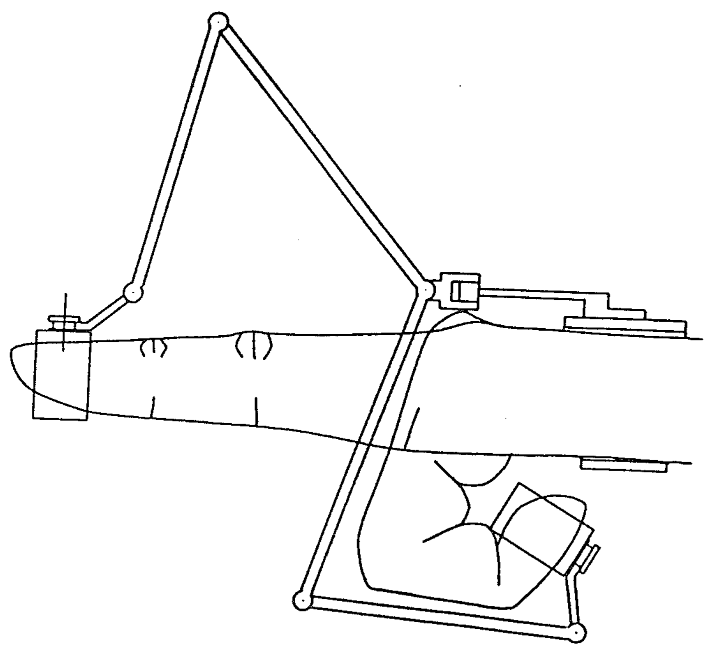

Figure 23. Mechanical Linkage Position Monitoring System

in Section 2.2.2.3. Table 7 shows a the results of a preliminary analysis of the maximum angles of rotation required at each of the joints of the linkage. This data is an important design requirement for the new rotational sensor invisioned for this device, as its effective angular range is limited.

Table 7. Rotational Specification of the Mechanical Linkage Position Monitoring Concept for a 50% Male

	Angle of Rotation
Distal	138°
Medial	34°
Proximal Pitch	121°
Proximal Yaw	+/-20°

For integration with an arm/wrist master controller the hand bracket would simply replace the hand grip on that controller.

2.1.3.2 Position monitoring research and development

Reasearch and development in position sensing focused on the "small optical rotational sensor". In addition a preliminary definition and assessment of the ultrasonic ranging system was conducted and a mockup of a portion of the "roller" concept of sensor integration was constructed.

2.1.3.2.1 Small optical rotational sensor

A small optical position sensor was constructed as described in Section 2.1.3.1.2. This consisted of a light source (LED) and a light sensor (phototransistor) separated by two pieces of polaroid plastic (See Figure 17). The amount of transmitted light, and therefore the output signal level varied with the relative angle between the polarization planes of the two polaroid sheets.

This demonstration model was constructed using threaded 0.5 inch plastic plumbing pipe as a case. Photograghs of the

preliminary prototypes are shown in Figure 24. The sized decreased dramatically with each prototype.

For the initial prototype (Figure 24a), the circuit used is shown in Figure 25. One disc of polaroid plastic was cemented to each half of the case, a standard red T 1-3/4 LED cemented in one end, and an OP800 phototransistor in the other. The phototransistor was baised into the center of its linear range with a 10 Megohm resistor and loaded in a common emitter configuration with a 15 Kohm resistor. The output signal was obtained from the collector. Rotating the two halves through 90 degrees caused the output signal to vary from approximately 1 to 4 volts when the device was powered with a six volt supply.

A smaller prototype version of the sensor was constructed using threaded brass fittings (see Figure 24b). A red T-1 LED was cemented in a 0.125 inch hole in one end and an OP800 phototransistor in a 0.156 inch hole in the other. Two polaroid discs approximately 0.2 inch diameter were used, one cemented to each half. As shown in Figure 26, the phototransistor was used in a common emitter configuration with a 100 Kohm load, but was left unbiased. The device was powered with a 5.00 volt supply and calibrated over a ninety degree range. The results of the calibration are shown in Table 8 and Figure 27. As expected, the overall output is non-linear, over the range 30 to 70 degrees it may be closely approximated by a straight line. Linearity is not a critical factor in any event if the device is to be used in conjunction with a computer to interpret the signal.

A third prototyupe was designed (Figure 24c), and constructed (Figure 28). This device was again much smaller, being only approximately 1/4 inch in diameter and length.

In its eventual production configuration the optical sensor device could be made much smaller yet. The LED and phototransistor are shown in Figure 29. They could be custom fabricated without the necessity of a bulky mounting, thus significantly reducing the length and diameter of the device. The polaroid plastic used in these models was 0.040 inch thick, but a thinner type could be used and bonded directly to the LED and phototransistor. The overall size could probably be reduced to less than 1/8 inch diameter by slightly over 1/8 inch long. The determining factor would most likely be the mechanical construction of the rotating joint.

Currents required by the device are small (approximately 30 mA to power the LED and much less for the phototransistor); thus lead wire size may be very small. To additionally reduce power consumption, the power to the device may be pulsed on for readings only. As the response time of the LED and phototransistor are on the order of microseconds, the average power consumption to even a large array of these devices could be reduced to an extremely small value.

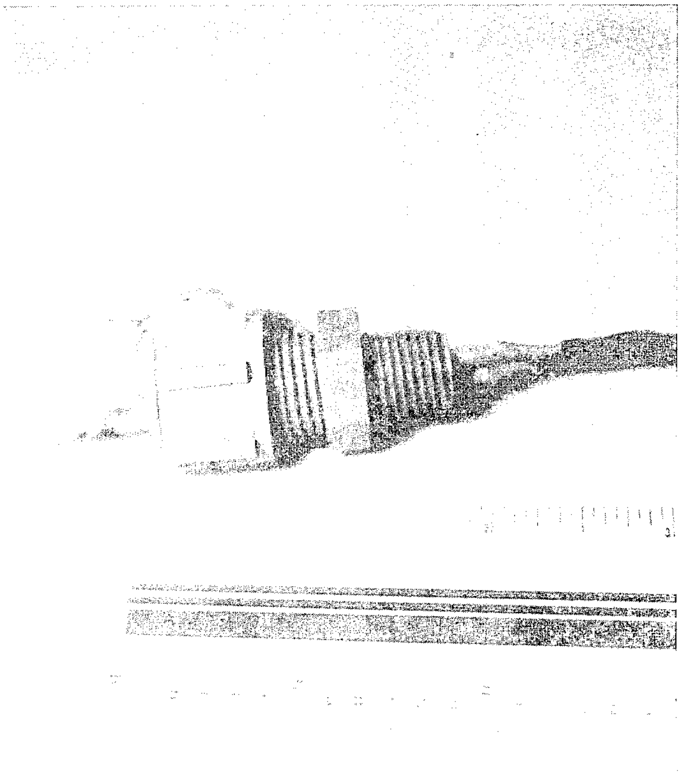

Figure 24a. First Prototype of ORBITEC Rotational Sensor

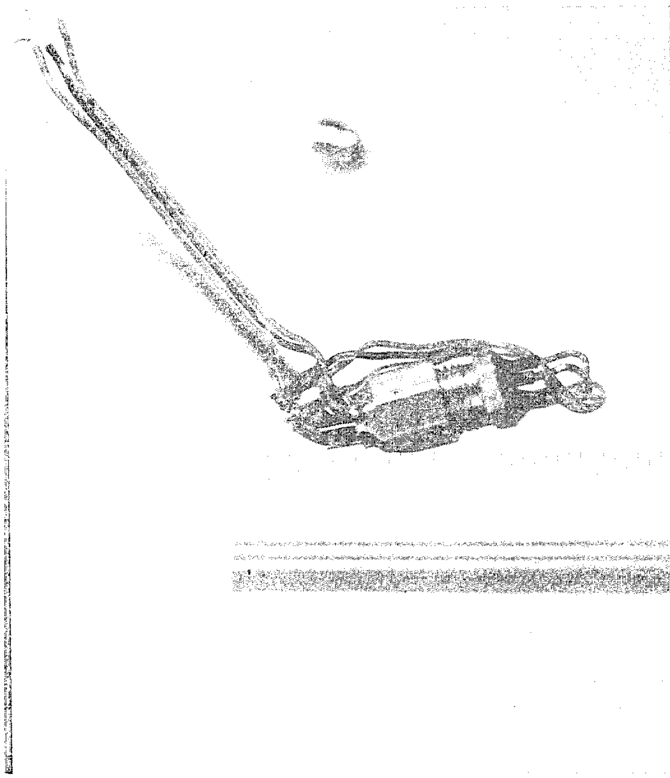

Figure 24b. Second Prototype of ORBITEC Rotational Sensor

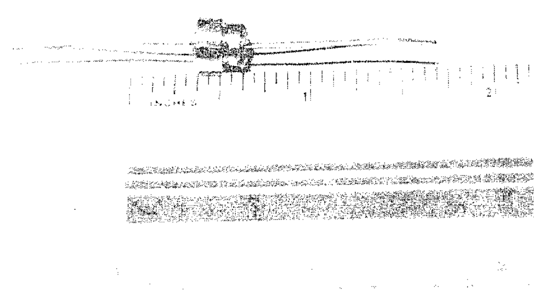

Figure 24c. Third Prototype of the ORBITEC Rotation Sensor

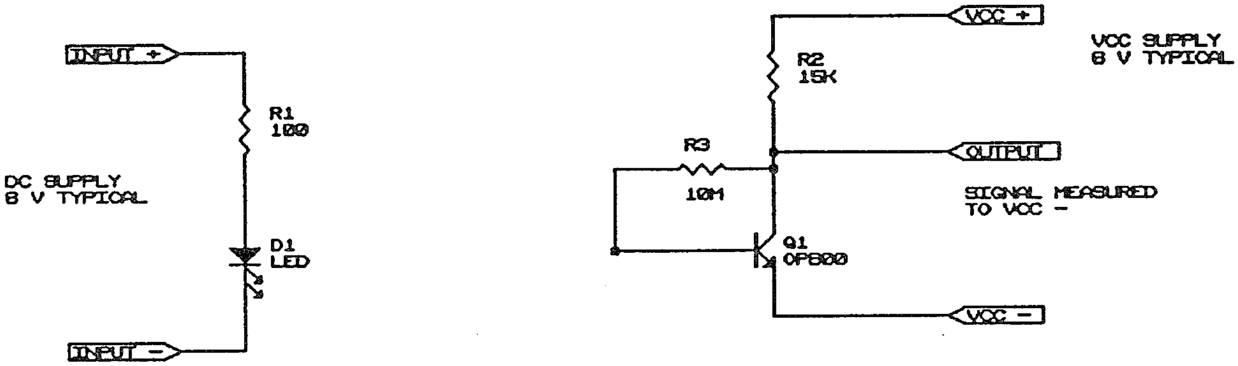

Figure 25. Electronics diagram for First Prototype of the ORBITEC Rotational Sensor

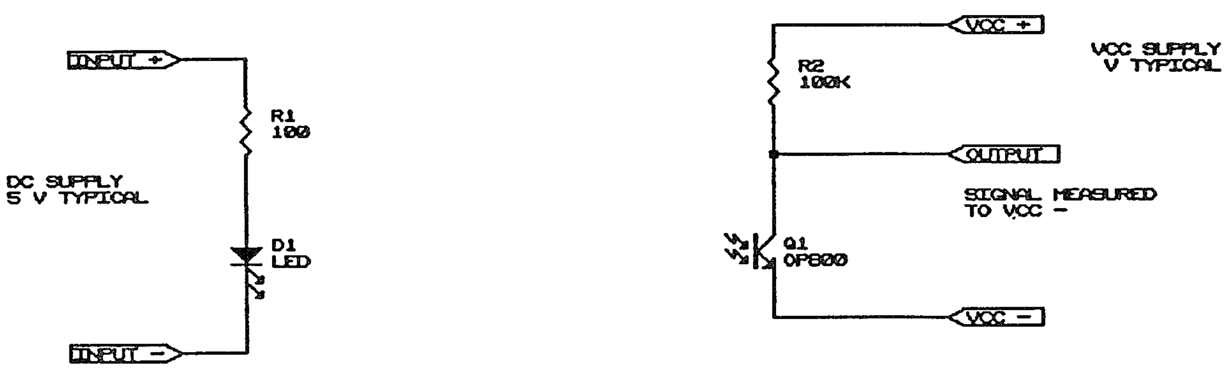

Figure 26. Electronics diagram for Second Prototype of the ORBITEC Rotational Sensor

Table 8. Preliminary response Data for the Second Prototype of the ORBITEC Rotational Sensor

ANGLE (deg)	OUTPUT (volts)	OUTPUT (normalized)
0	0.218	0.045
5	0.222	0.046
10	0.230	0.048
15	0.243	0.050
20	0.310	0.064
25	0.594	0.123
30	1.05	0.217
35	1.45	0.300
40	1.90	0.393
45	2.38	0.492
50	2.89	0.597
55	3.32	0.686
60	3.73	0.771
65	4.06	0.839
70	4.37	0.903
75	4.60	0.950
80	4.78	0.988
85	4.82	0.996
90	4.84	1.000
95	4.81	0.994
100	4.72	0.975
105	4.57	0.944
110	4.32	0.893
115	3.78	0.781

Supply voltage = 5.00 volts.

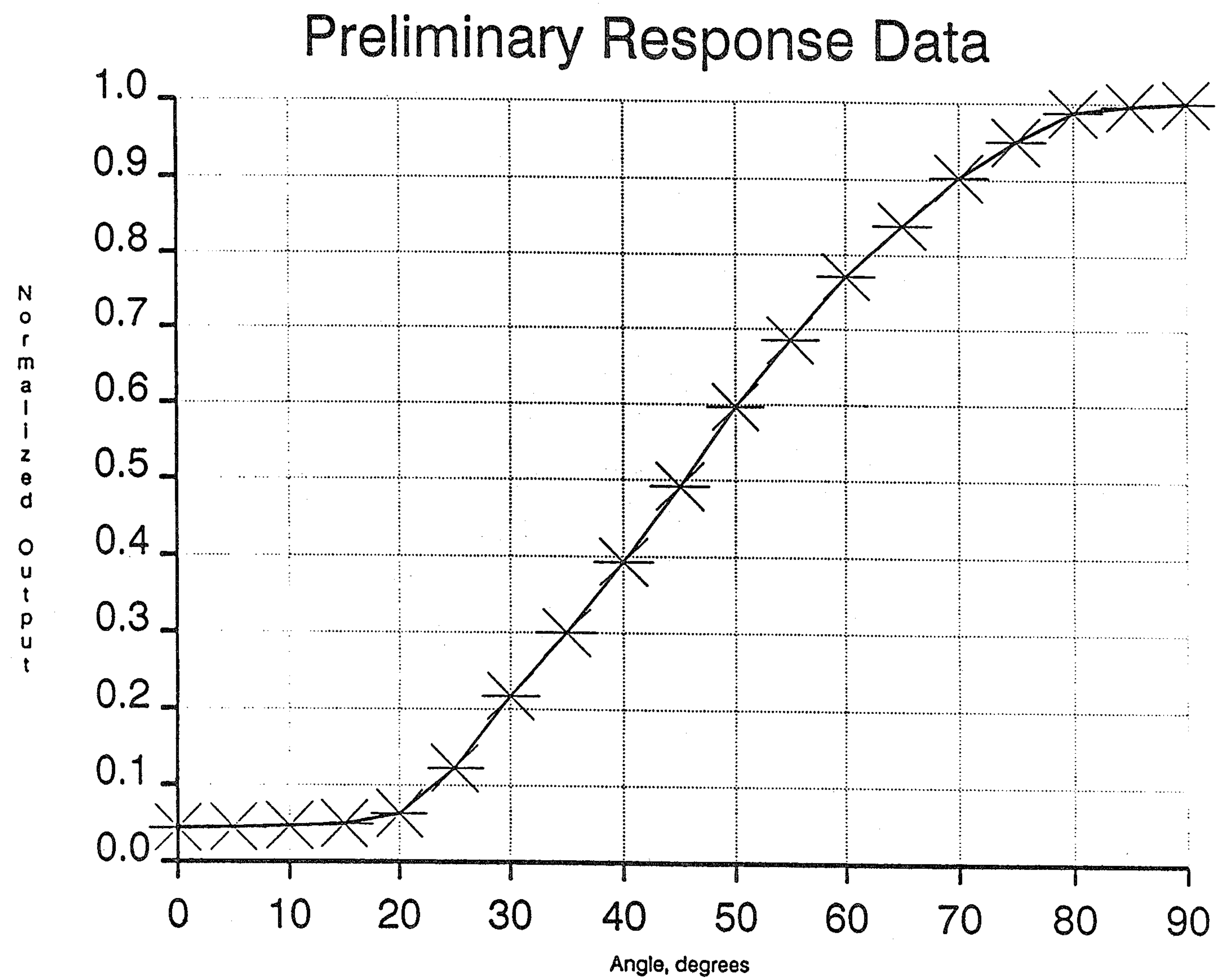

Figure 27. Plot of Preliminary Response data for the Second Prototype of the ORBITEC Rotational Sensor

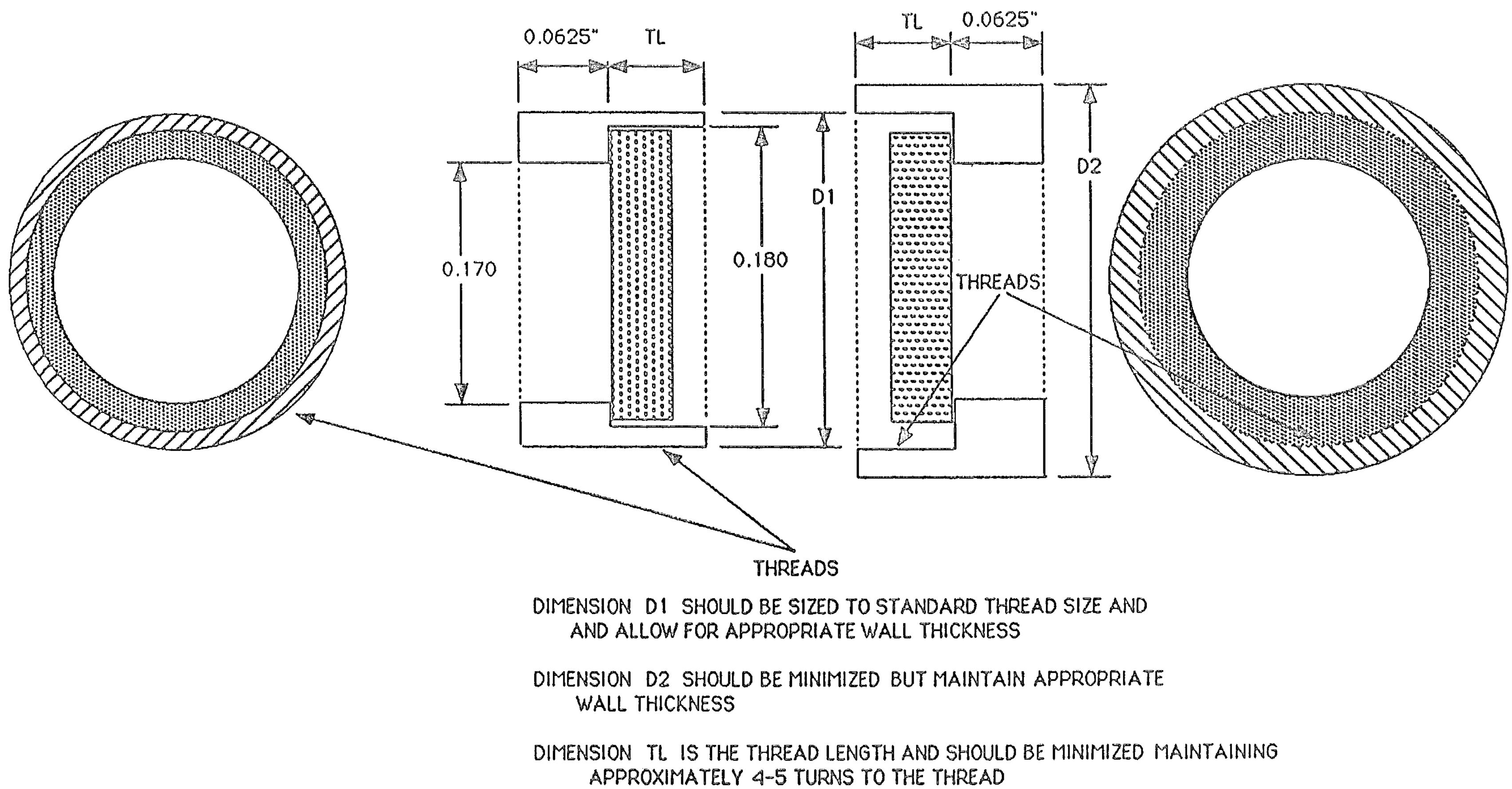

Figure 28. Preliminary Design Crawing of the Third Prototype of the ORBITEC Rotational Sensor

Figure 29. Photograph of the LED and Phototransistor Mounted on a T-1 Header

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The mechanical loading of the measured angle would also be very small. Again, depending on the mechanical construction of the sensor case and rotating joint, the torque require could be reduced to a very low level. This, coupled with the low mass of the sensor itself, would provide for minimum interference with the device to which it is attached.

The optical position sensor demonstrated by this work represents a potential for an accurate, low cost, small measurement device. Over the central range it closely approximates a linear device; however, it offers sufficient resolution over the entire ninety degree range if non-linearity is acceptable. The device is physically small, low power, produces a relatively large output signal, and may be connected with three leads. If an array of these sensors is used only a single additional lead wire is required beyond the first device. If an array of n devices is used, the power consumption may be reduced by pulsing. In this case a total of square root n plus one lead wires is required.

If the rotation angle range exceeds the linear range of the sensor, linearity can be maintained by utilizing two of these very small sensors. This approach was used in applying this sensor to

the "mechanical linkage" concept for position measurement. This design is presented in Section 2.2.2.3.

2.1.3.2.2 Ultrasonic ranging system

The basic theory of the ultrasonic ranging system is similar to an area navigation system. Three receivers are located at known spots in the area of the master hand. A transmitter for ultrasonic pulses is attached to the fingertip of each finger of the glove. (If the slave end effector has only 3 fingers, for example, then only three fingertips of the master glove would have transmitters.) A pulse is sent from a finger tip and received at each of the three receivers. By measuring the time the pulse is re[illegible] receiver and comparing this to the time of transmission, the range between each receiver and the fingertip may be calculated if the speed of sound is known. The system is shown in simplified form for one finger in Figure 30.

In practice, the glove fingertips need have only an ultrasonic transducer which may be connected to pulse generating circuitry controlled by a computer. The receivers would also be controlled

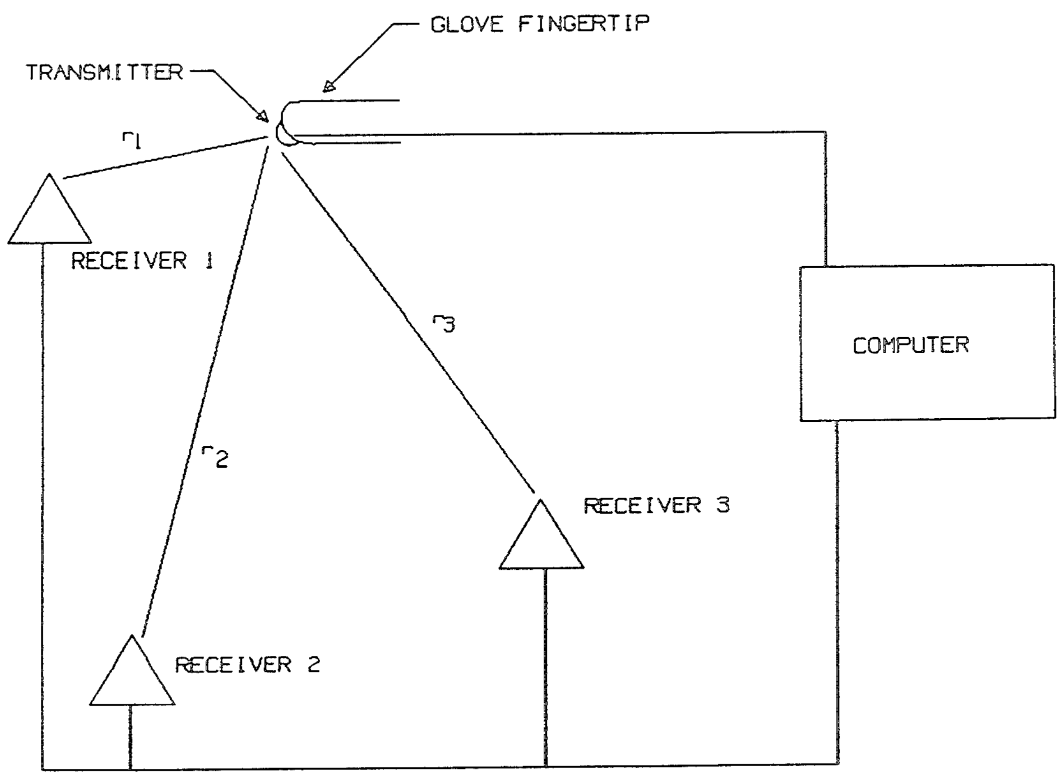


Figure 30. Ultrasonic Position Measurement System

by the same computer. Thus the computer could generate a pulse for the first finger, measure the receive times and calculate the slant range, and then repeat the process for each of the other fingers. Because the response time of the hand is relatively slow it is possible to multiplex in this manner with no significant loss of position accuracy during the measurement cycle. To compensate for variations in the speed of sound due to changes in temperature, density, etc., an additional transmitting transducer may be located a fixed distance from the receivers. The transmitter is pulsed in the sequence with the glove fingertips and the actual transmission speed calculated from the known distance and the measured receive times.

The receiving stations would be located within a partically enclosed area to prevent interference from outside sources and objects. The operator would then don the master glove and place his hand within this area. This system is similar to a glove box, but would not require the tight seal. The reference transmitter and each fingertip of each of the operator's two gloves would be pulsed in sequence and the receive times at each receiver would be measured by timing the first received pulse. This is done to prevent confusion from echos. The computer can be programmed to ignore any pulse after the first for some fixed period of time. By careful choice of receiver location within the box, the chance of an echo with a shorter transmission path than the primary pulse may be eliminated.

If it develops that some hand positions could cause a pulse to be blocked and thus go undetected by one or more receivers, additional receivers may be placed at other locations within the box so that at least three will always be able to receive a pulse directly. Because only three unknowns must be calculated (x,y, and z position if space) any three of the receivers could provide the information necessary to determine the fingertip position.

With the transit times involved of sonic velocities, measurements may be easily made to provide position accuracy of 1-3 mm. Because the final positioning of the slave is accomplished using tactile and/or force feedback, this precision is more than enough.

It should be noted that the concept as described above provides control only for two degrees of freedom of finger closure. It does provide control for finger yaw. Very effective dextrous slave hands can be designed with only two degres of freedom in finger closure. Typically the distal joint is linked to the medial joint providing closure motion closely modeling the natural closure motion of the human hand. The ultrasonic concept could be extended to three degrees of finger closure by adding additional transmitters on other links of the fingers.

2.1.3.2.3 Roller concept mockup

Figures 2.1.3-20 and 2.1.3-21 show a rough mockup of the "Roller" position monitoring concept. These figures illustrate how the rollers wrap around the knuckle as the hand closes. As noted previously, a tendon would be wrapped around the rollers and attached to the back of the hand. The function of the rollers is to provide compliance for the back of the finger mounting whole also providing joint angle measurement.

2.1.3.3 Position monitoring evaluations and comparisons

Table 9 compares the various position sensors considered for the OTCG. The new optical rotation sensor developed by ORBITEC satisfies requirements for accuracy and stability and is the only sensor small enough for the OTCG. It therefore became the sensor of choice. It was used in all subsequent design, analysis, and development work in this Phase I Project. However, the ultrasonic ranging system represents a very unique and interesting alternative that is recommended for further investigation in Phase II.

2.1.3.3.2 Sensor integration evaluations and comparisons

Table 10 compares the various sensor integration options previously identified. Concepts are compared with respect to accuracy , repeatability, ease of operator hand mount/attach, sensor requirements and other factors. The "mechanical linkage" concept was selected for the OTCG because it provides a unique combination of attributes not available in any other concept. It can accurately and reliably determine finger configuration, is relatively easy to mount/attach, and is readily integrable with wrist/arm master controllers.

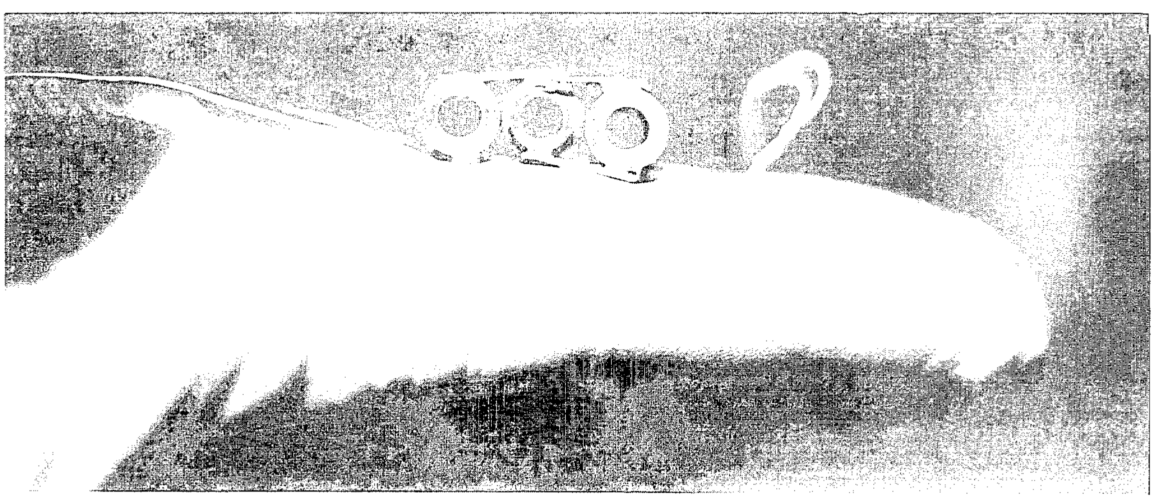


Figure 31. The Roller Position Monitoring Prototype - Straight Finger

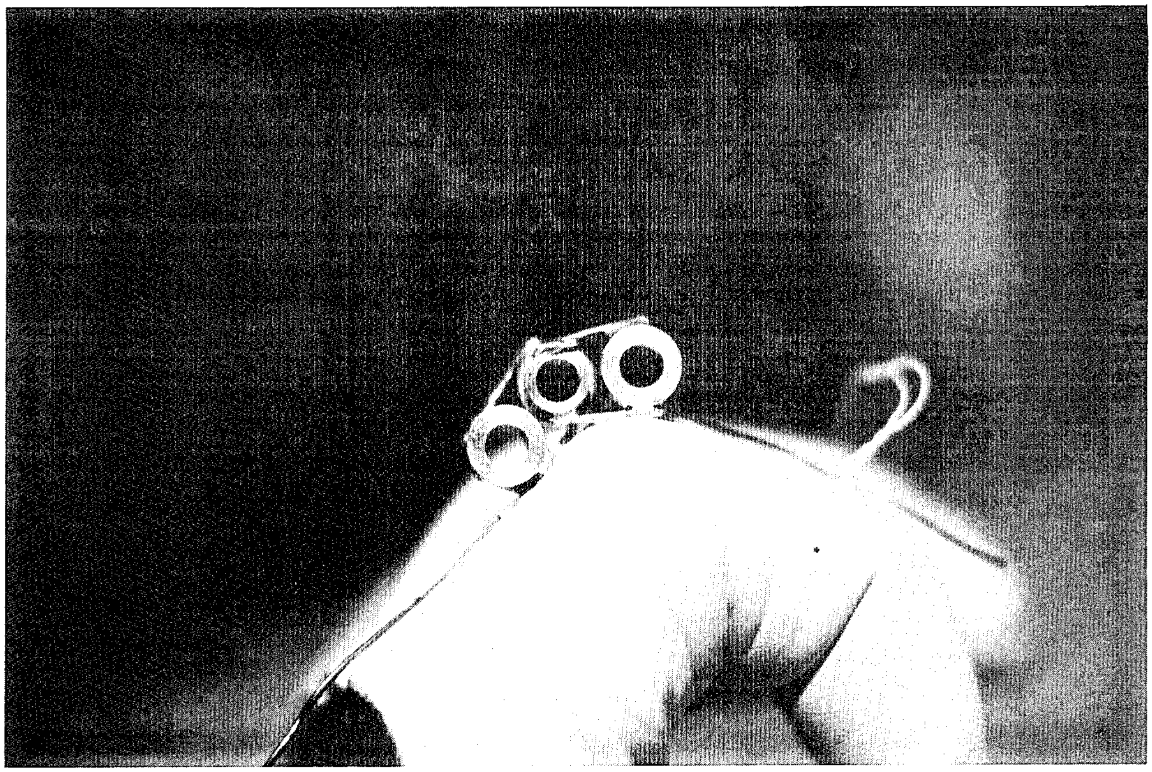


Figure 32. The Roller Position Monitoring Prototype - Bent Finger

Table 9. Comparison of Position Sensors for the OTCG

TYPE	APPROXIMATE SIZE	LIFE	APPROXIMATE RESOLUTION	RANGE
TRIM POTENTIOMETER	0.25 in dia	200	< 1 deg	270 deg
INSTRUMENT POTENTIOMETER	0.5 in dia	1-20 million	<< 1 deg	360 deg
OPTICAL ENCODER	0.75 to 3.0 in. dia	>> 1 million	< 0.1 deg	360 deg
MAGNETIC	0.6-0.75 in. diameter	> 1 million	1-15 deg	360 deg
LIGHT PIPE (VPL GLOVE)	0.12 in. x 3 in.	?	1-5 deg	90 deg
SYNCHRO RESOLVER	1-2 in. dia	>> 1 million	0.01 - 0.1 deg	360 deg
LVDT	0.25 in.	> 100,000	< 0.01 in.	0.3 in.
OTC ROTATIONAL SENSOR	0.1 in.	>> 1 million	< 1 deg	80 deg

TABLE 10. SENSOR INTEGRATION COMPARISON CONCEPT

ADVANTAGES	DISADVANTAGES	
Flexible Link	Adaptable to a large range of hand sizes	Power grip may have some restrictions
	Approx. 90^0 rotation per sensor	Many attachments required
	Easy to fit onto an operator	Difficult to prevent slippage
	Moderately low profile	Accuracy, repeatability unclear
Roller	Low profile (no hardware above fingers)	Difficult electrical cable routing
	Less than 90^0 rotation per sensor	Cumulative error on sensors
		cannot achieve proximal yaw angle
		Accuracy, repeatability unclear
		Spring loc. Unsuitable
		Spring force varies with position
Cable/Sheathing	Low profile (no hardware above fingers)	Spring loc. unsuitable
		Spring force varies with position
		Difficult mounting/ attachment
		Accuracy, repeatability unclear

TABLE 10 SENSOR INTEGRATION COMPARISON (CONTINUED)

CONCEPT	ADVANTAGES	DISADVANTAGES
A.D. Little/Exos	Adaptable to many hand sizes	Power grip may have some restrictions
	Less than 90^0 rotation per sensor	High profile
	Accurate, repeatable	Many attach points
Mechanical Linkage	Mounts to fingertips only	Very high profile
	Adaptable to many hand sizes	More than 90^0 rotation per sensor
	Accurate, repeatable	Power grip may have some restrictions
	Readily integrates to wrist/arm controller	

2.2 System design

A preliminary system design for the ORBITEC Telerobotic Control Glove (OTCG) was generated based on system and subsystem requirements and the results of component development activities. The design was taken through a preliminary design review (PDR) near the end of the project.

The overall system design was developed based on the use of selected components. This design process considered the available test beds and subsystems, the demonstration requirements of the SBIR, and eventual system development direction. A basic architecture was selected and required special interface devices developed.

2.2.1 Requirements

The requirements for the OTCG were carefully examined. Based on the results of this effort, a preliminary design specification for the OTCG was drafted and is presented below.

OTCG PRELIMINARY DESIGN SPECIFICATION

The Orbitec Telerobotic Control Glove (OTCG) shall be designed to provide telerobotic control of dexterous robotic end effectors. It will include position control and feedback of tactile, force, and torque information to the human operator. It will incorporate sufficient degrees of freedom to control dexterous fingered hands. It includes the following major components: glove with integrated mechanical elements, stimulators, position sensors, interfaces, and software.

Glove

(1) The glove must provide a good fit (minimal slippage) for hands ranging from the 5th to 95th percentile

(2) The glove must be comfortable to wear for extended periods up to 8 hours

(3) Don/doff of the glove shall be possible with ease

(4) Glove shall be totally and permanently integrated with electromechanical devices such that no assembly is required

(5) Emergency doffing in 5 seconds or less will be possible.

Stimulators

(1) Normal and shear force information shall be presented to the palm side of the hand. Torque information shall be

presented as a combination of force and shear information

(2) A minimum of two modes of stimulation feedback must be provided

(3) A standard interface must be provided such that any sensor output can be configured to activate stimulator response.

Position Sensors

(1) Joint position must be measured to an accuracy of 1.0 degrees

(2) Must be stable (no drift)

(3) Position readings must be repeatable to accuracy of (1)

(4) Must survive 100,000 cycles without degradation

(5) Mountable on glove mechanical design

(6) Size goal is diameter less than 1/8 inch, length less than 1/4 inch

(7) Must produce no friction perceivable to operator.

Software

(1) Provide standard output of joint angles

(2) Receive standard input of tactile, normal, and shear force information.

Interfaces

(1) Joint angles output shall be standardized to a 0-10 volt output per joint

(2) Tactile, normal, and shear force shall be standardized as a 0=10 volt input.

2.2.2 Glove Mechanicals

The glove mechanicals provide the operator physical interface to the position control system and the vibratory display system. This interface must maintain consistent contact with the operator's hand, minimizing slippage and rotation between the operator and the OTCG.

2.2.2.1 Glove overall system design

The overall OTCG system design includes a fitted glove which maintains the vibratory displays positioned on the operator's hand, a position monitoring linkage which is attached to the fitted glove via a quick disconnect, electrical cabling, and an interface for attachment to arm/wrist controllers. The fitted glove and the position control linkage are attached through a quick disconnect mechanism such that rapid mounting and dismounting can be accomplished. The fitted glove will have its own electronic cabling with quick disconnects at the arm\wrist interface. The position monitoring linkage is rigidly connected to the arm\wrist interface and contains its own electronic cabling. Each of these areas is described below.

2.2.2.2 Fitted Glove Design

The purpose of the fitted glove is to provide a snug fit to the operator's hands such that no slippage or rotation occurs of the operator's hand with respect to glove and position monitoring device. The fitted glove will be put on by the operator hand and linked to the position monitoring linkage through a quick disconnect device at the tip of the finger. The glove shall include a semi-rigid cap on the fingertip such that this quick disconnect mechanism can be installed. Also integrated with the fitted glove design will be the vibrational stimulator arrays. Several size gloves shall be available to fit nearly any size hand. The number of sizes required to span the fifth percentile female to the ninety-fifth percentile male size range will be driven by the design and integration of the stimulator arrays into the fitted glove.

Vibrational stimulation to the hand requires a consistent mechanical resistance between the glove and the operator's hand without movement of the stimulators across the hand surface. Thus,

a fairly snug fit is desired for this glove. However, the fit must also be loose enough and comfortable enough such that an operator can wear the glove for up to eight hours or more. The current configuration of the fitted glove is designed after the comfort gloves used by astronauts inside the space suit glove. The glove is made of a nylon mesh which allows comfortable wearing for several hours while providing a relatively tight fit to the operator hand. The fabric is also lightweight and durable. The weave allows air movement to the hand to avoid the generation and buildup of perspiration. A prototype of the fitted glove is shown in Figure 33.

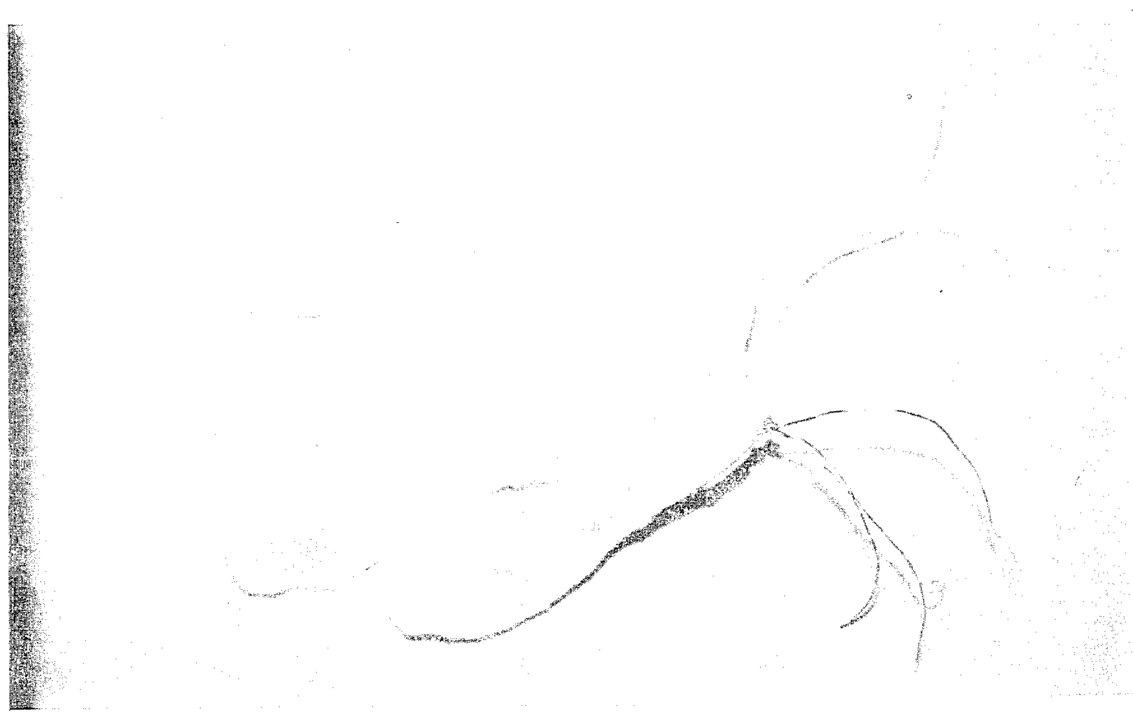


Figure 33. Prototype of the OTCG Fitted Glove

The stimulator arrays will be directly integrated into the glove such that the proper stimulator location is automatically achieved once the glove is put on by the operator. The preferred stimulator arrays, previously shown in Figure 4, will be directly sewn to the upper and lower surface of the fitted glove. The layer shown in Figure 4 as the diaphragm will actually be the glove fabric. The stimulator arrays will be interfaced to avoid joint areas of the glove where fabric overlap occurs. The rigid backing of the stimulators will help to eliminate fabric overlap over the stimulator arrays.

For the purpose of a quick ingress, the operator may put on the fitted glove thus applying the stimulators to the surface of

his/her hand. In another move, the glove may be easily attached via the fingertips to the position monitoring linkage. Should an emergency occur, the quick disconnect between the fitted glove and the position monitoring linkage can be disconnected by a quick twist and the glove electronics disconnected via a tug from the arm/wrist interface. The operator is then free to continue emergency procedures and manipulations with the fitted glove on. Should the glove be encumbering, the operator may remove the glove in a third movement.

Each stimulator array shall require at a maximum ten wires. The number of wires may be reduced to six should a matrix multiplexing approach be used (see Section 2.2.5.2). The wires from each stimulator array will be cabled together down the finger and across the top part of the hand where they are collected into a single-bound multi-wire cable which is attached to the arm/wrist interface via a quick disconnect linkage. The electronic input of the stimulators shall be standardized (e.g. -5 to +5 volts) such that any sensor can be used to drive the stimulators in the desired fashion. This will give great flexibility in applying the OTCG to existing or future slave devices with varied sensing capabilities.

2.2.2.3 Position monitoring system design

The following describes the exoskeletal mechanism for finger joint angle monitoring. This device will detect unique finger positions and finger joint angles, and send the appropriate commands to the controller for the slave dexterous hand mechanism.

2.2.2.3.1 Position Monitoring Objectives and Considerations

The objective of the mechanism design is to provide accurate finger joint angle information with minimal intrusiveness to the operator when conducting dexterous movements of his/her hand. This requires that the mechanism have minimal weight, provide non-constrained movements of the fingers, be comfortable to wear and have minimal friction, stiction, backlash, and out of axis motion. Additionally, other objectives include minimal manufacturing difficulty, rapid ingress and egress of the hand to and from the controller, compactness, and the flexibility to be used over a large range of hand sizes.

A critical design objective involves operator comfort. If the operator fatigues rapidly when operating the mechanism, it is essentially an ineffective mechanism. To provide adequate comfort, it is necessary that the mechanism couple to the operator's hand with minimal blood flow restriction to the outer regions of the hand from the attachment location. Therefore, it was decided to minimize the amount of attachments to the hand and distribute the load over a large surface area where attachments do occur. Additionally, it is necessary that the coupling of the mechanism to the hand be passive without requiring finger pressure to

maintain position, since the fingers are no longer free to be used for gripping of the mechanism as in pistol grip or joy stick designs commonly used on present teleoperated systems.

2.2.2.3.2 Position Monitoring Linkage Design Description

The master hand controller mechanism design that was developed is represented in Figures 34, 35, and 36 representing side, top and rear views, respectively, for one finger of the mechanism. The mechanism consists of a 4-axis, exoskeletal linkage system that primarily resides above the hand. Joint angle sensors are located in each joint of the mechanism. Knowledge of the mechanism joint angles and the link lengths provide sufficient information to determine the joint angles of the finger.

Hand Interface.

Coupling to the operator is in keeping with the above operator comfort criteria. Effectively, two areas of contact are used to attach to the hand. Coupling to the finger is accomplished by through a snug fitted finger ring (integrated into the fitted glove) for the distal link of the finger. This ring must be sized to an individual operator and will be sized appropriately for the various fitted glove sizes. The Quick disconnect mechanism shall allow for attaching and detaching the fitted glove to the position monitoring linkage.

The "U-shaped" bracket not only couples the master hand controller to the operator's hand but also acts as the interface to a master "arm" controller (see Section 2.2.2.4). This coupling is critical since it is expected that the master arm/wrist controller may likely be a force reflecting type master providing reaction forces to the operator. It is necessary for operator comfort that the forces be distributed over the hand surface without extreme high pressure localization.

Two methods have been established for attachment of the "U-bracket" to the back and palm areas of the hand that provide adequate force distribution. The first method involves using Polyform Modeling Compound which is molded to an individual's hand. It is a flexible material with the consistency of clay which is inserted between the operator's hand and the "U-bracket". Once it is molded it is heated and permanently set. This provides a snug distributed load over the hand. However, this method is not viewed as a long term solution since it requires that a mold be made for each individual operator.

A long term solution involves the use of a compartmentalized inflatable bladder between the "U-bracket" and the operator's hand. This bladder may also be integrated into the fitted glove. The operator can inflate the bladder to obtain a snug but comfortable fit. This method not only would allow for a range of different

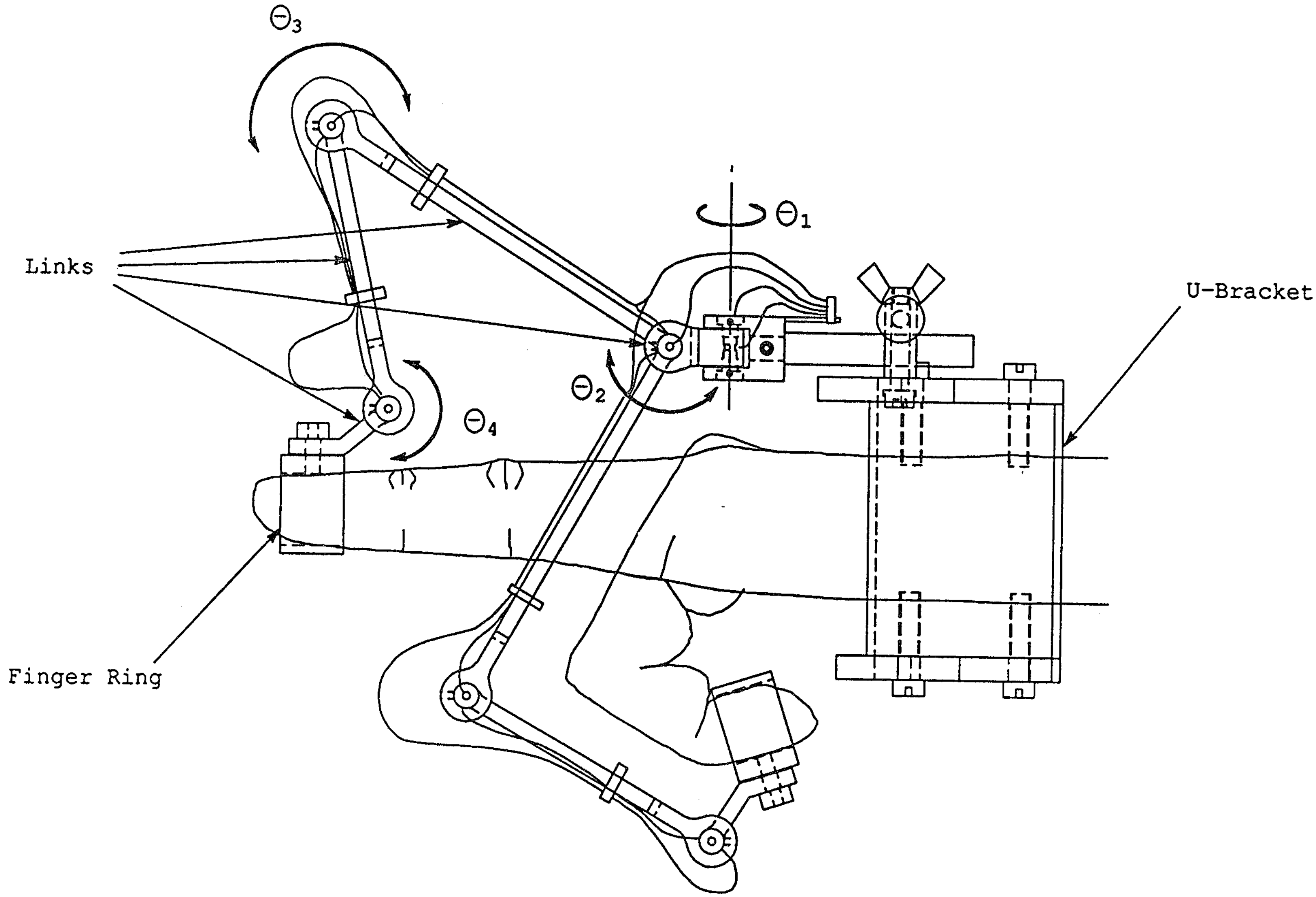


Figure 34. Side View of the ORBITEC Master Hand Controller

OTCG-I FINAL REPORT

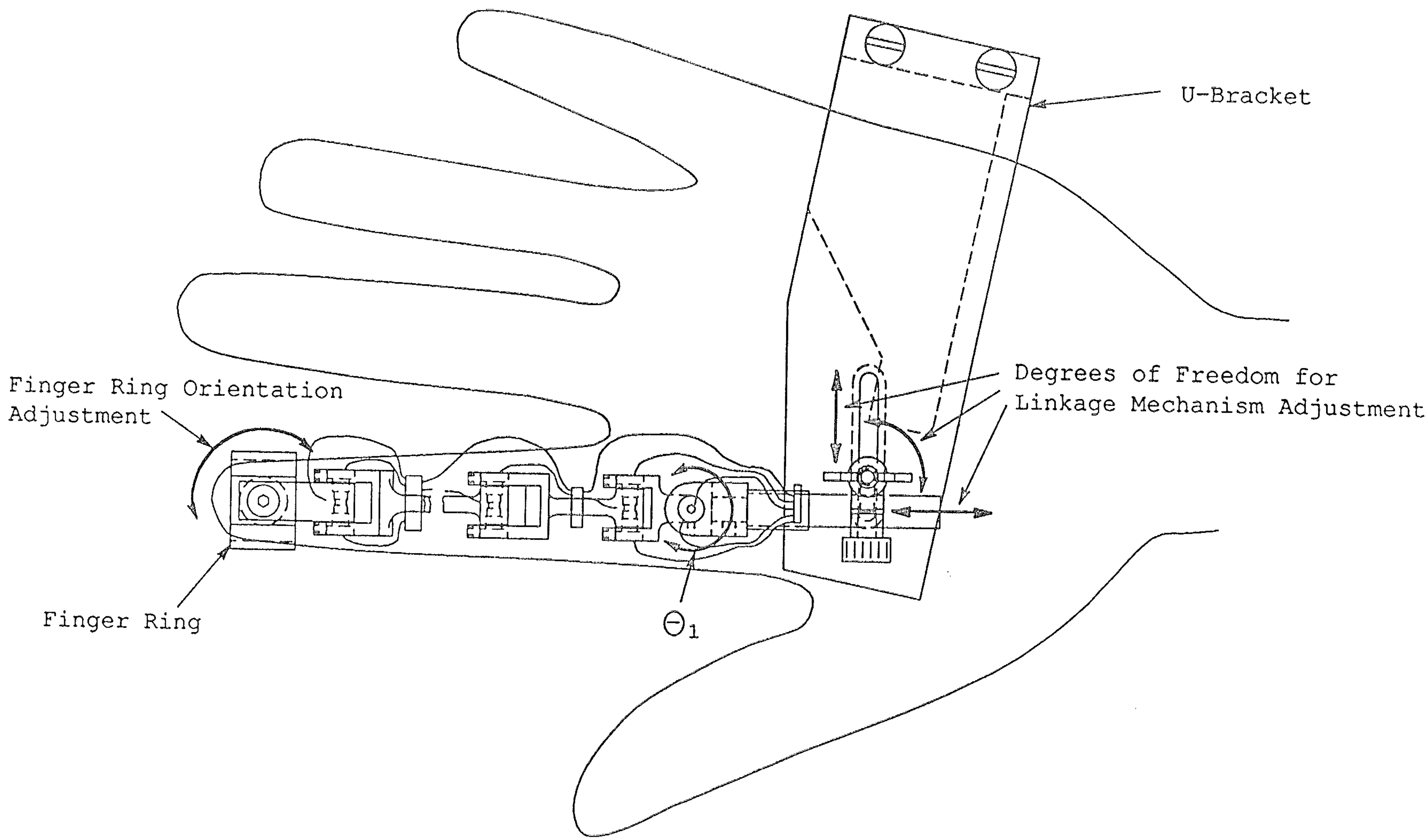


Figure 35. Top View of the ORBITEC Master Hand Controller

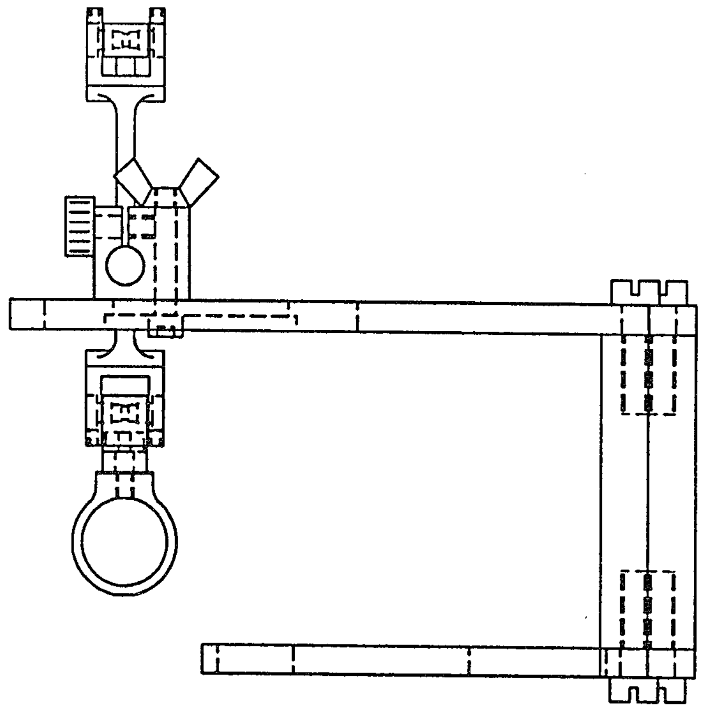


Figure 36. Rear View of the ORBITEC Master Hand Controller

size hands, but allow rapid ingress and egress of the hand to and from the master controller. Detailed design of this bladder will be accomplished in Phase II of this project.

There are two critical adjustments necessary when the master controller is fitted onto the hand. The first axis, Q1, of the linkage mechanism must be coincident to the first joint (yaw axis of the proximal joint) of the finger. Three degrees-of-freedom are provided for this adjustment as shown in Figure 35. Another adjustment required is the orientation of the finger ring to the linkage mechanism, also shown in Figure 35.

Materials.

For weight reduction purposes, the material selected for the links and finger ring is Vespel SP-211, a thermoplastic material. This material was primarily selected for its weight, friction, and bonding characteristics.

Minimum weight is desirable to minimize the inertial forces imposed on the operator's fingers during acceleration and deceleration. Since there is sliding contact at the joints connecting the links, a material with a low friction coefficient is desirable to reduce finger motion resistance. Vespel SP-112 is frequently used as a bearing material. It has a dynamic friction coefficient of 0.12 and a static friction coefficient of 0.20 with sliding contact against the same material. Since the joint angle sensors are integrated into the links, bonding of the sensor components to the link is required, consequently, a material with good bonding characteristics is desirable. Suitable adhesives exist on the market for bonding Vespel SP-112 for integration into the fitted glove.

The majority of the other components may be made of aluminum, such as the "U-bracket" and connecting components between the "U-bracket" and the finger linkage.

Sensor Integration into the Links

To provide a compact design, the joint angle sensor components have been directly integrated into the links as shown in Figure 37. Incorporated into Link A are the two light sources which are bonded to the link. Two polarizing discs are also bonded to this link above (and below) the light sources. Bonded to each Joint Pin are a polarizing disc and a photo transistor. Link A and Link B are connected together using the two Joint Pins. Set screws are provided to retain the Joint Pins to Link B. The size of the rotational sensors represents the size of the most recent prototype developed in the laboratory and discussed in Section 2.1.3. Great reductions in size of this rotational sensor are anticipated which will allow some degree of shrinkage of the linkage joint components.

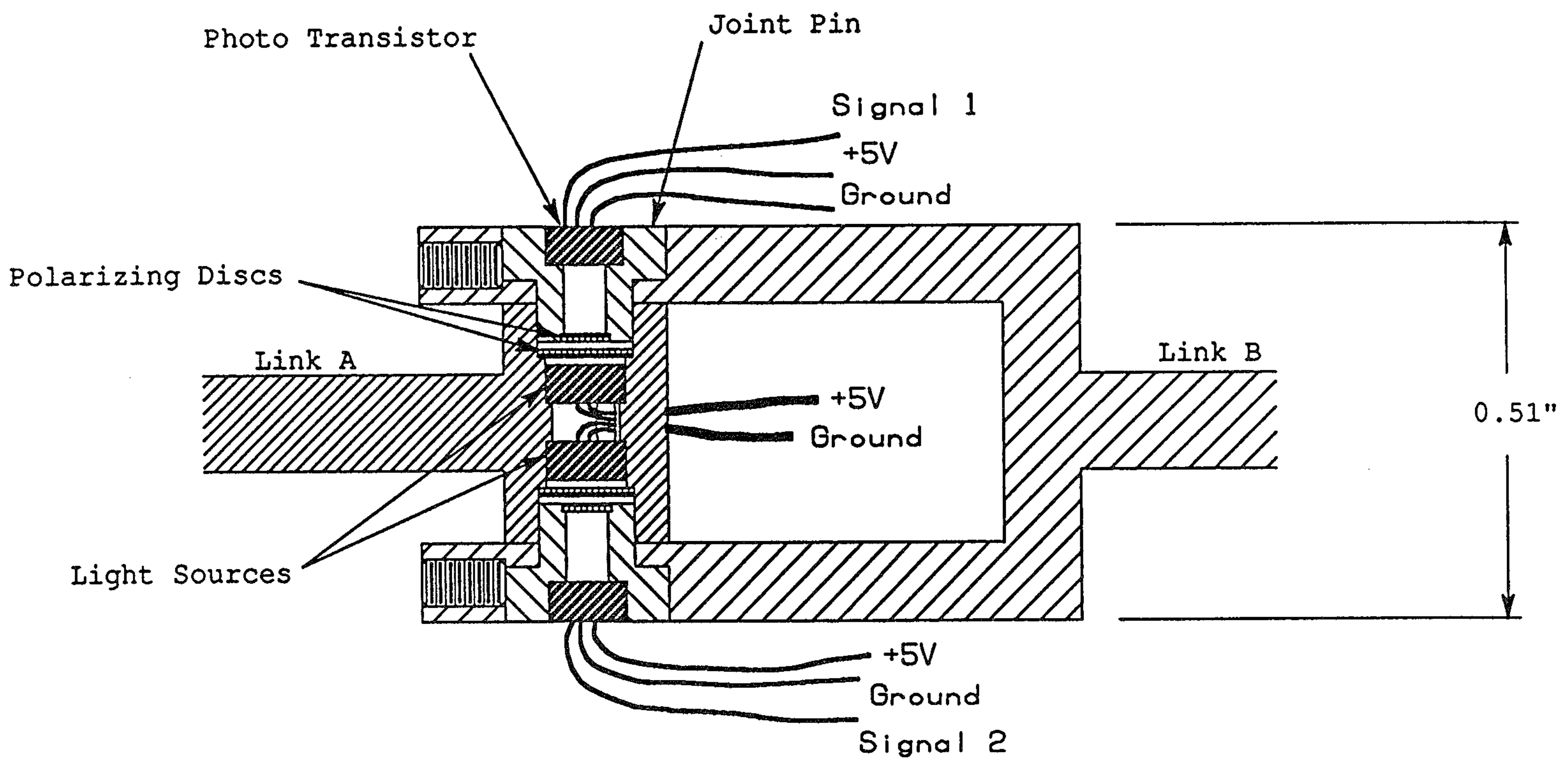


Figure 37. Cross-Section of Joint Illustrating Joint Sensor Components

OTCG-I FINAL REPORT

2.2.2.3.3 Kinematics

The kinematics of the mechanism are described in this section. Using the joint angles information from the mechanism, the position and orientation of the finger tip in the world coordinate system is easily obtainable and subsequently, a geometric solution to the finger joint angles is achievable. The mechanism with its coordinate frames is illustrated in Figure 38. The Denavit-Hartenberg parameters for the mechanism are given in Table 11. Using the D-H parameters and substituting in known values for the mechanism link lengths, the position of the finger tip in the world coordinate system can be calculated from the following equation:

$$[P]^w = [T]_1^w [T]_2^1 [T]_3^2 [T]_4^3 [P]^4 \qquad [1]$$

This simplifies to:

$$[P]^w = [T]_4^w [P]^4 \qquad [2]$$

Table 11: Denavit-Hartenberg Parameters

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	l_1	θ_1
2	-90	l_2	0	θ_2
3	0	l_3	0	θ_3
4	0	l_4	0	θ_4

The first finger joint angle (yaw angle of the proximal joint) can be obtained directly from the first axis of the master controller since these two axes are coincident. The rest of the linkage is planar and plane geometry techniques can be applied to directly find a solution to joint angles of the finger axes. Again referring to Figure 38, the finger tip orientation can be found from the following equation:

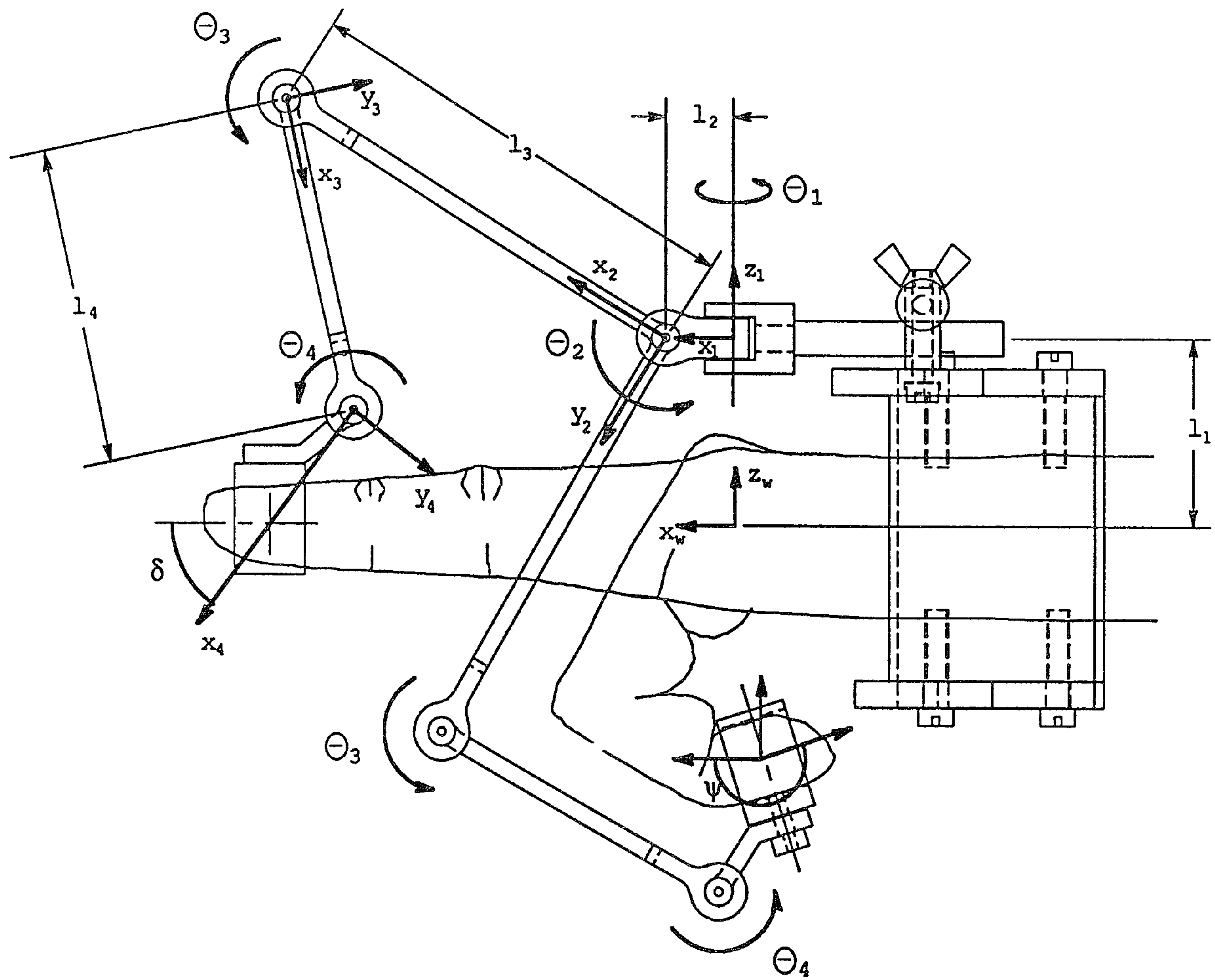


Figure 38. Coordinate Frame Assignment for ORBITEC Master Hand Controller

$$\psi = \theta_2 + \theta_3 + \theta_4 - \delta \qquad [3]$$

Referring to Figure 39, and applying the "law of cosines" the finger joint angles (2, 3 and 4) can be found from the following equations:

$$\alpha_3 = 180^\circ - \beta_2, \qquad [4]$$

where

$$\beta_2 = \cos^{-1}\left[\frac{a^2 - f_1^2 - f_2^2}{-2f_1f_2}\right], \qquad [5]$$

$$a^2 = f_3^2 + x^2 + z^2 - 2f_3\sqrt{x^2+z^2}\left[\cos(\psi - \beta_1)\right], \qquad [6]$$

$$\beta_1 = \tan^{-1}\left(\frac{-z}{x}\right). \qquad [7]$$

$$\alpha_2 = 90^\circ - \beta_3 - \beta_4 - \beta_5, \qquad [8]$$

where

$$\beta_3 = 90^\circ - \beta_1, \qquad [9]$$

$$\beta_4 = \cos^{-1}\left[\frac{f_2^2 - f_1^2 - a^2}{-2\,f_1\,a}\right], \qquad [10]$$

$$\beta_5 = \cos^{-1}\left[\frac{f_3^2 - a^2 - \left(x^2+z^2\right)}{-2\,a\sqrt{x^2+z^2}}\right]. \qquad [11]$$

where

$$\alpha_4 = 180^{\circ} - \beta_6 - \beta_7, \qquad [12]$$

$$\beta_6 = 180^{\circ} - \beta_2 - \beta_4, \qquad [13]$$

$$\beta_7 = 180^{\circ} - \beta_5 - (\psi - \beta_1). \qquad [14]$$

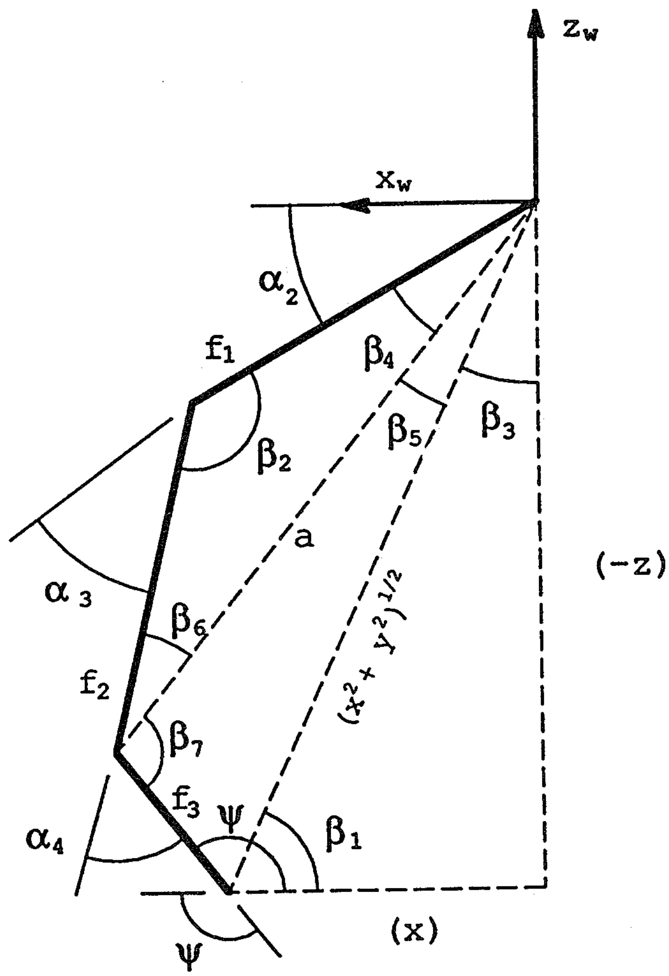


Figure 39. Plane Geometry Associated with the Last Three Axes of the Finger Linkage

2.2.2.3.4 Prototype Development

A laboratory prototype of the master hand mechanical linkage has been built. The prototype did not include integration of the actual joint sensors but was built to verify the feasibility of using such a mechanism as a hand controller and sized accordingly. The primary issues of concern were to verify the methods of attachment to the hand, determine if any restrictions or resistance to finger movements existed, and verify general overall operator comfort. The prototype has proven to be a valuable tool and a series of recommendations are discussed in the following section resulting from testing conducted on the prototype device.

A series of photographs of the prototype is shown in Figure 40. It is primarily made out of 2024-T3 aluminum alloy. Special emphasis was placed on providing sufficient adjustments in the linkages so as to fit a large range of hand sizes.

We have concluded from the demonstration and testing of the position monitoring linkage that this is a viable method to be pursued for obtaining finger joint angle registration. There seems to be sufficient operator comfort when operating the prototype mechanism.

There is a minor amount of restriction in finger movement on the yaw axis of the finger. This is a result of the movement of the last three joints of the finger not representing planar motion, while the mechanism is configured for planar motion for these joints. It is felt that some compliance between the finger ring and the finger linkage would reduce this restriction. On the other hand the restriction is minor enough that it may not necessarily be a problem. Based on the prototype testing, it is concluded that providing finger linkages for additional fingers would just be a matter of adding additional finger linkages. This is also the case for the thumb although some additional brackets and modifications would be required to the "U-bracket" for attachment of the thumb linkage.

Further recommended developments include:

* build a joint with the sensor components integrated to verify the integrity of the joint design.
* pursue the design of a bladder as the interface between the hand and the master controller.
* investigate an automated calibration procedure for quickly obtaining the operator's finger link lengths.
* build a passive compliant joint between the finger ring and the finger linkage.
* build a complete master controller for one finger with all the sensors integrated to check the accuracy of the finger joint angles.

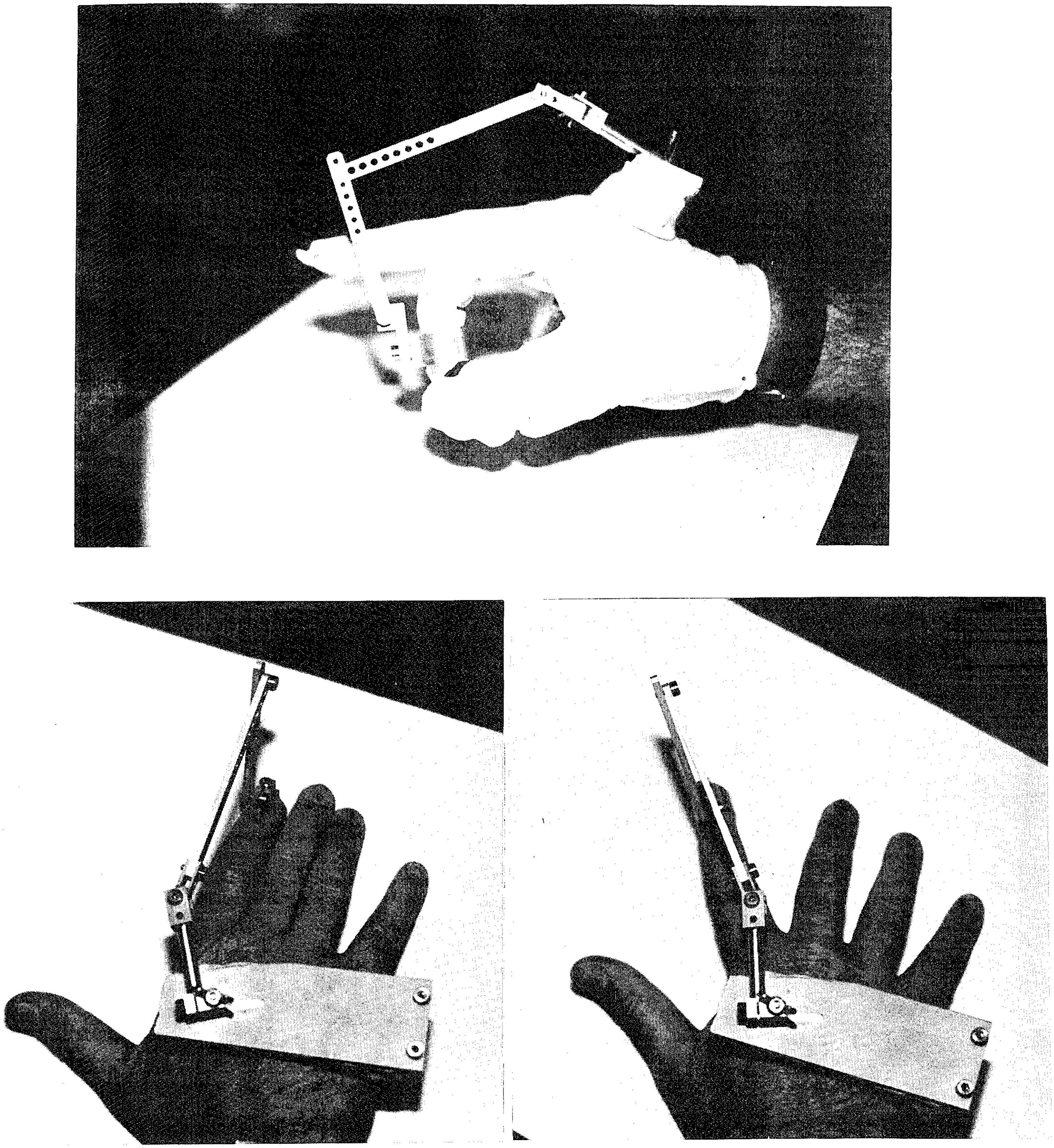
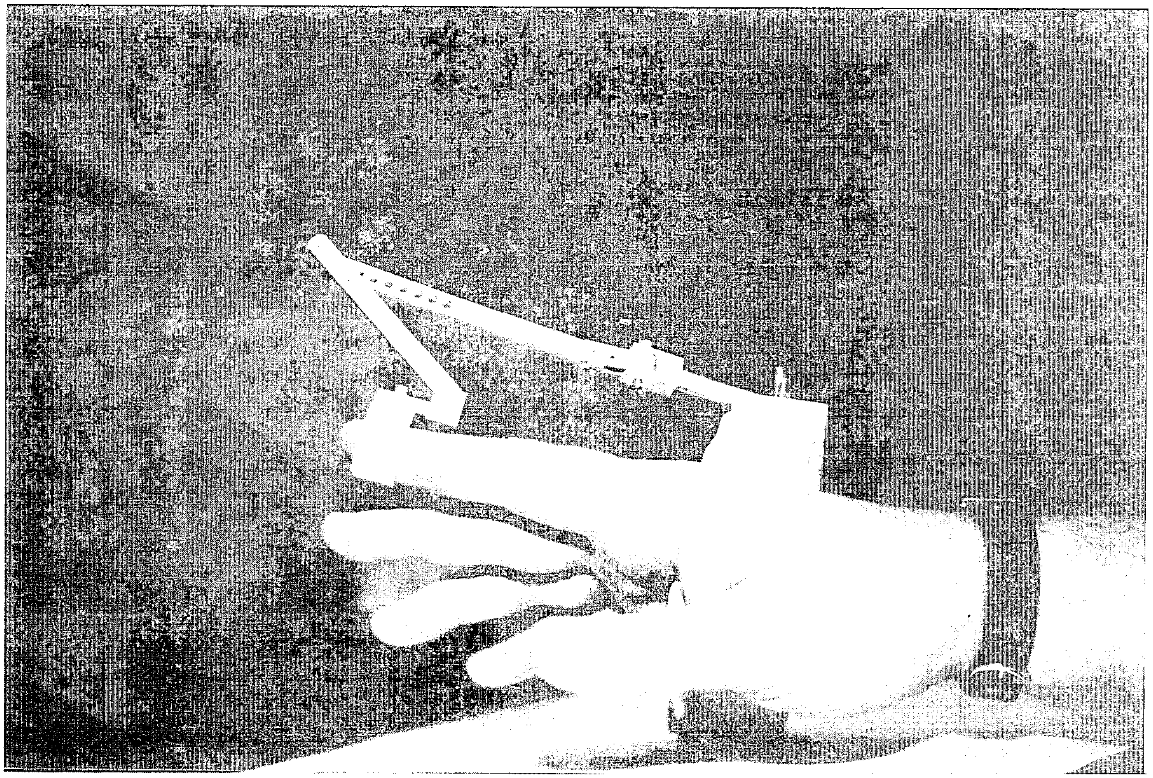


Figure 40. Photographs of the ORBITEC Master Controller Prototype



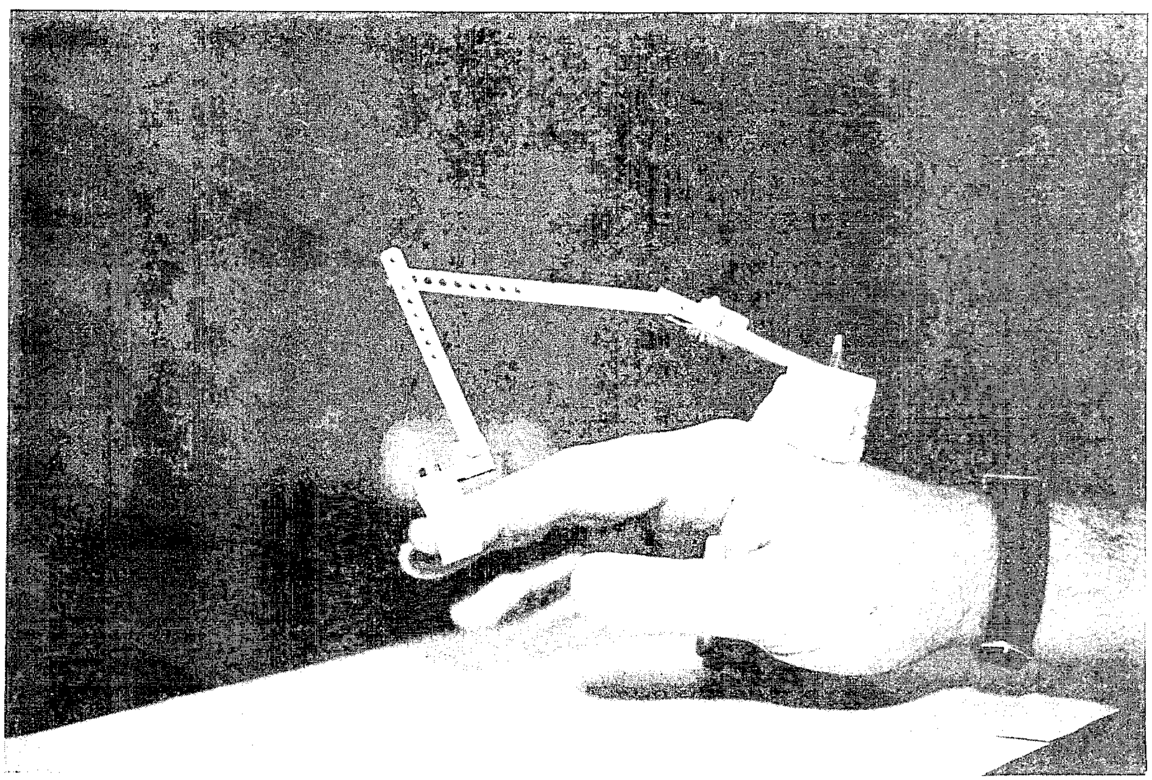


Figure 40. Photographs of ORBITEC Master Controller Prototype, cont.

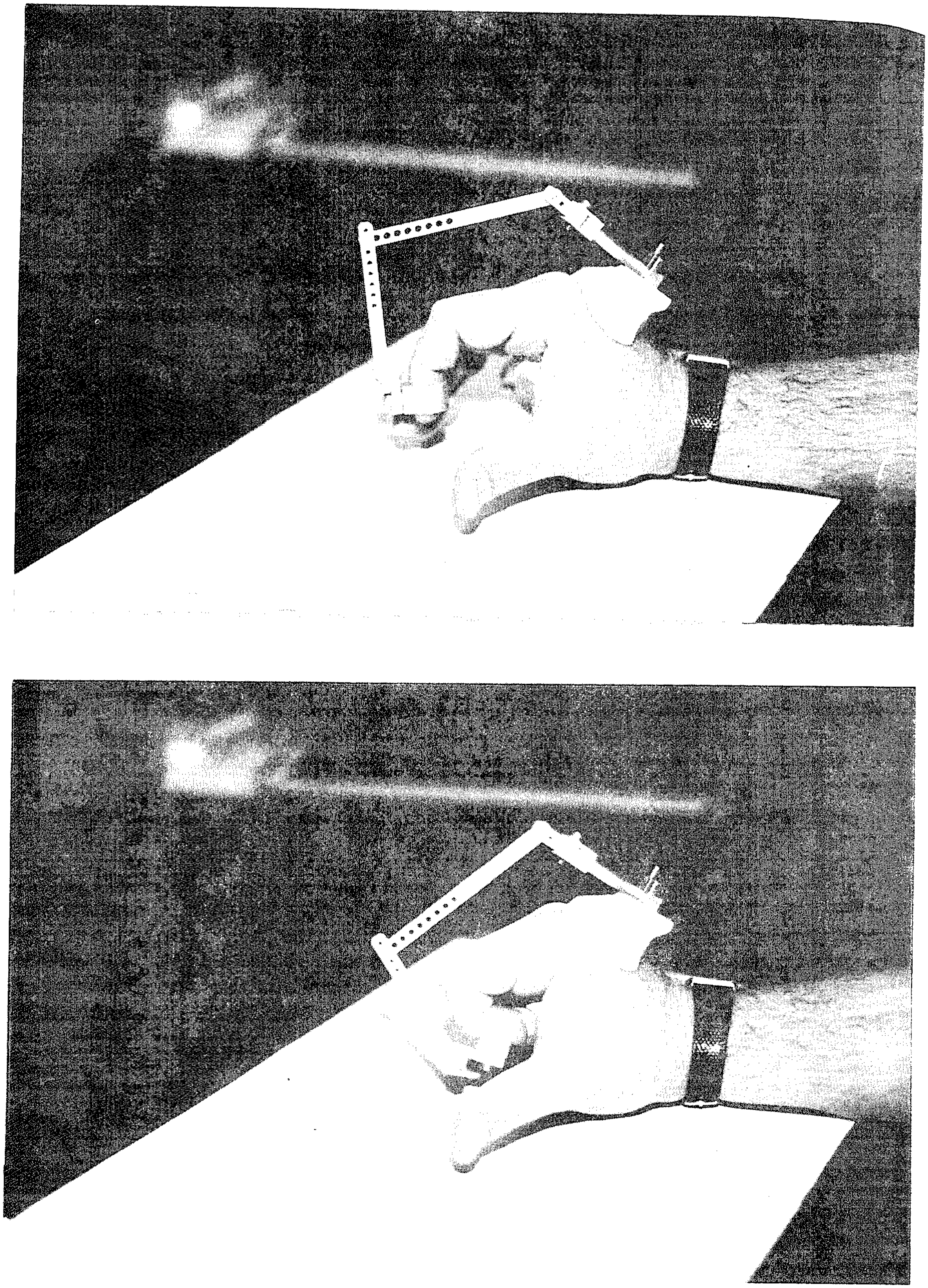


Figure 40. Photographs of ORBITEC Master Controller Prototype, cont.

Section 2.2.2.4 Arm/Wrist Interface Design

A rigid arm/wrist interface is provided for the OTCG to be attached to a telerobotic arm/wrist controller. This interface is mechanical only; no electrical connections are required although they could be integrated if desired. The interface is provided in the base palmar area where the position monitoring linkage device is firmly attached to the hand and palm. This allows for a solid, rigid interface to the operator such that the operator can impart and receive force and torque information from the arm/wrist controller (assuming the arm/wrist controller is force reflective in nature). It is this interface that provides the OTCG with great versatility as a complimentary capability to existing arm/wrist telerobotic control devices with advance dexterous manipulators.

2.2.3 Computer/control architecture

Figure 41 illustrates a schematic of the entire control glove system as it would be applied to control of a robotic slave hand. Information and commands translate between the glove and hand via a PC/AT class computer. The positions of the joints of the glove are monitored by sensors. This information is transmitted to the host PC in a digital format (an analog/digital, "A/D", converter is required if the sensor output is analog). The PC converts position commands of the glove to the joint space of the robot hand and position, commands are subsequently sent to a motion controller. The motion controller is designed and programmed to convert joint commands to motor control voltages which are amplified in a power amplifying motor driver (with power supply) and delivered to the motors. Position information is transmitted back to the motion controller. The controller closes the position control loop driving the errors between commanded joint angles and measured joint angles to zero. The controller also adds required compensation for stabilizing the system.

Tactile sensors attached to the fingers of the robot hand will sense forces applied to any object the fingers are in contact with. They will transmit analog voltage signals proportional to forces sensed. These signals will be routed through a power amplifier and A/D converter to the host PC. The PC will convert this information into appropriate commands for the stimulator arrays in the control glove. The output digital commands of the PC will be routed through a D/A converter to a power amplifying stimulator driver. The driver then will power the stimulators providing the human operator with vibrational stimuli proportional to forces and tactile contacts being experienced by the robot hand.

All of the major componentry (PC, A/D and D/A converters, motion controllers and drivers) is available commercially. A dedicated host PC was used for this development effort but most of its functions will be downloaded into the motion controller for position/force control and a dedicated microprocessor for stimulator control in the operational system.

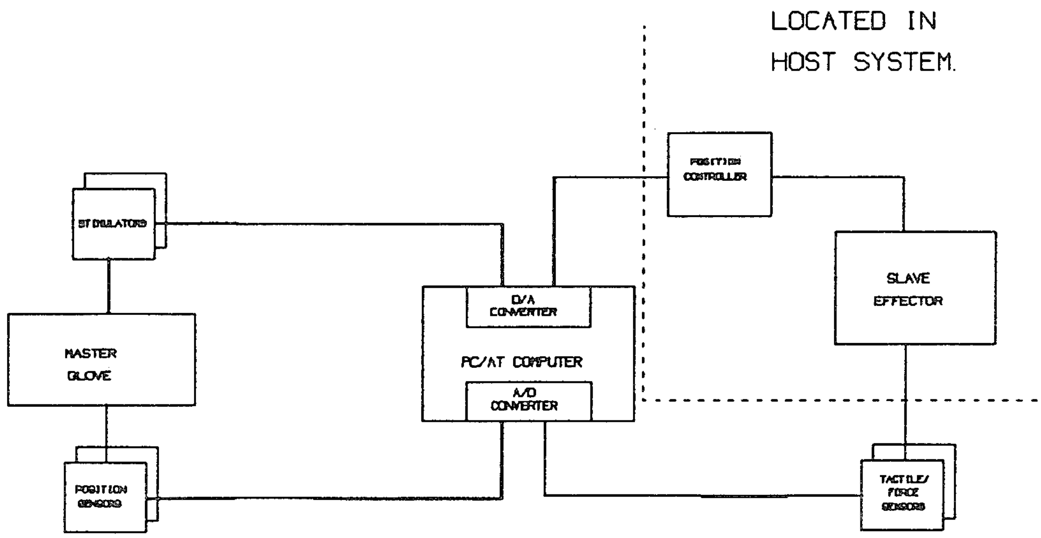


Figure 41. General System Architecture

2.2.3.1 Baseline Architecture Definition. The baseline OTCG test configuration is shown in Figure 42. Actual control of the slave effector is provided by the PC/AT in an open loop manner with desired position control signals derived from the glove position sensors. Feedback information to determine the actual final position of the slave is obtained through the operator from visual and tactile information. Force/tactile information is derived from sensors located on the slave effector while visual information is provided by direct observation.

The system uses the PC/AT type computer as a central processor. This processor can provide any necessary data processing beyond that which is done in the signal conditioner and driver circuits. In this way more complex transformations, such as are required for the force resolution of a three axis force sensor, would be possible. Additionally, this processor can provide control processing to the degree necessary. How much, if any, control processing is required depends on the particular configuration in which the system is used. For this Phase I activity the OTCG stimulator system was tested in the WCSAR test bed and position control was accomplished by a WCSAR PC in the test bed.

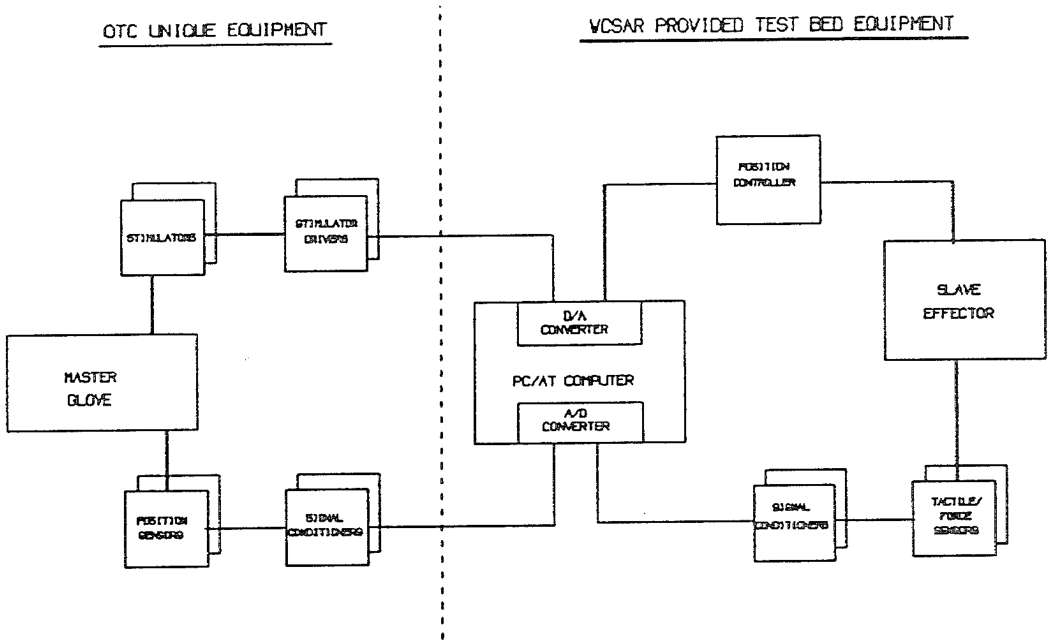


Figure 42. Test Configuration Architecture

The PC/AT was equipped with Analog to Digital (A/D) input boards and Digital to Analog (D/A) output boards. At least eight channels of A/D and four channels of D/A were provided. The A/D boards accept inputs at +/- 2.5, 5.0, +/-5, or 10 volt levels. Input ranges of +/- 10 mV and 20 mV were provided for maximum flexibility.

The PC/AT was equipped with 8 channels of digital, or "on-off", input and output. An RS-232 port was provided for communication with other computers.

Signal conditioner are needed to provide any necessary excitation signals to a sensor and to modify the range or type of output signal from the sensor in such a way that it is compatible with the input channels of the computer without destroying any of the desired information.

A generalized signal conditioner, as shown in Figure 43, was defined. This device would allow for interfacing between sensors (master hand position and tactile/force) and the PC/AT. A signal conditioner of the type shown allows for a maximum of flexibility during design in that it can handle inputs from a number of different types of sensors and produce and output signal compatible

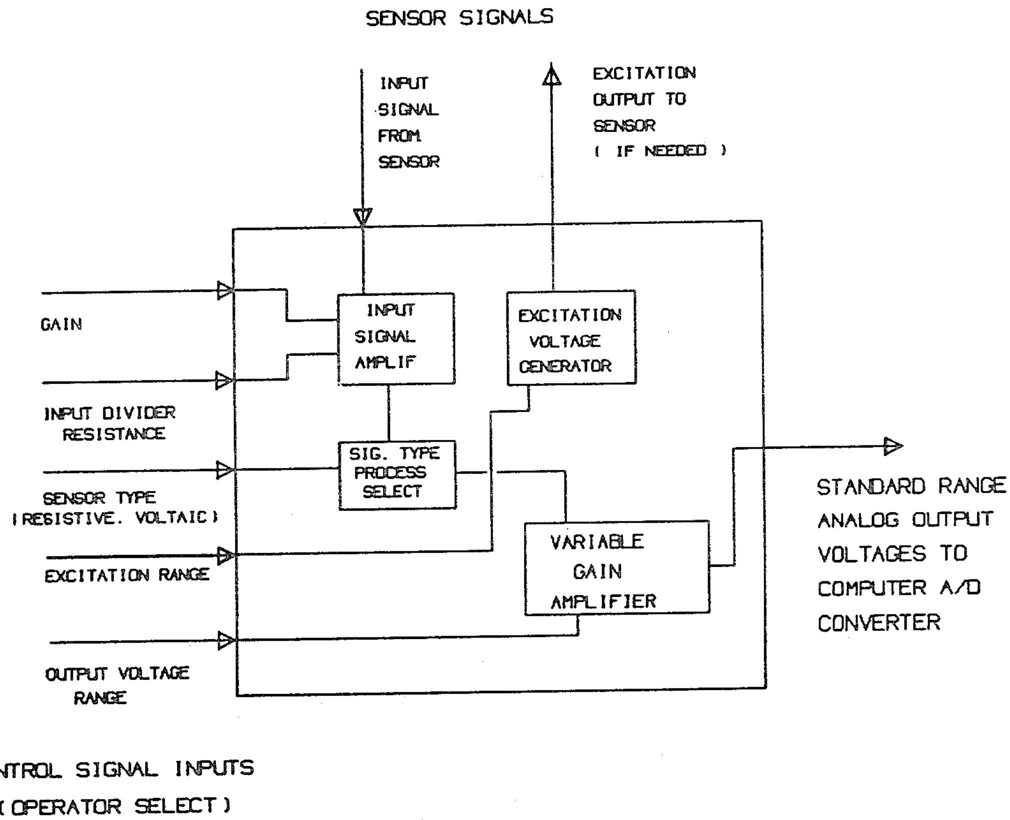


Figure 43. Generalized Signal Conditioner

with the A/D boards of the computer. Design should be relatively simple and cost low. Each sensor will require its own signal conditioner: however, once a sensor type is chosen, a less complex signal conditioner can be designed for that particular unit.

Once the tactile/force information has been obtained from the sensors on the end effector, it must be converted to a form which can drive the stimulators in the master glove. Any necessary coordinate transformation or other complex mathematical processing are performed within the PC/AT. Any simple level changes are kept external to the computer. This allows a standardized output signal (0 to 5 volts, for example) to drive the stimulator. Such a standard signal is obtained from many systems without the necessity of going through the OTCG PC/AT. This proved to be of benefit in the testing conducted in the WCSAR testbed. The WCSAR controlling system already had the force information available.

It is desireable to combine both the tactile (0-0.75 pound) and force (0.75-5 pound) information into a signal supplied to one stimulator. Because the response of the hand to vibration may not be able to resolve fine differences in amplitude over the entire 0-5 pound range, it was decided that two aspects of the stimulator signal be varied. As shown in Figure 44 and 45, the stimulator driver was designed so that both the amplitude and frequency of the

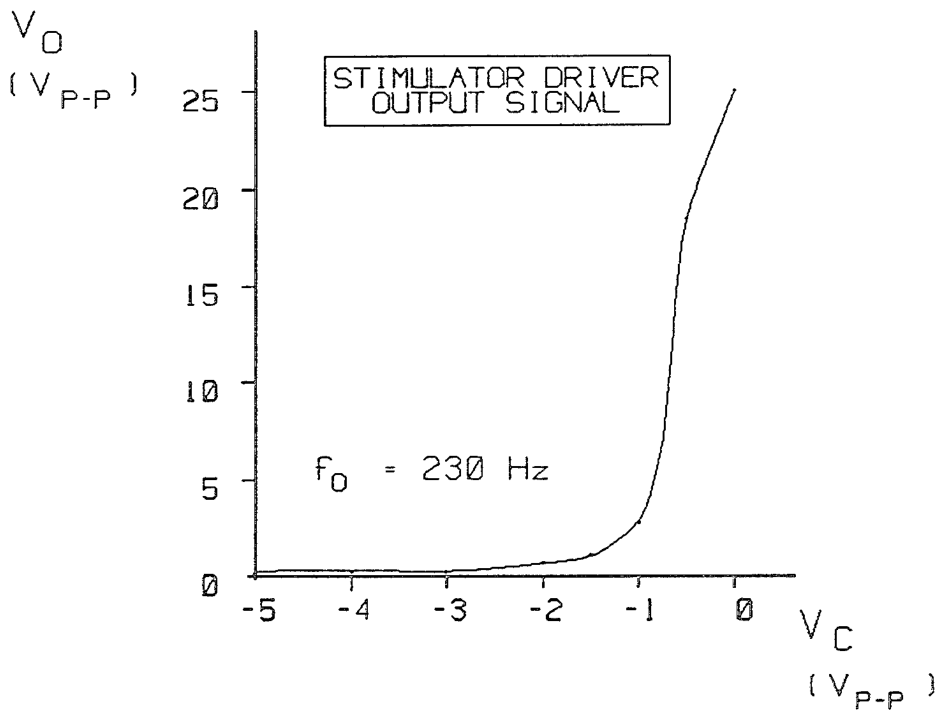


Figure 44. Stimulator Driver Response - Low Level Input

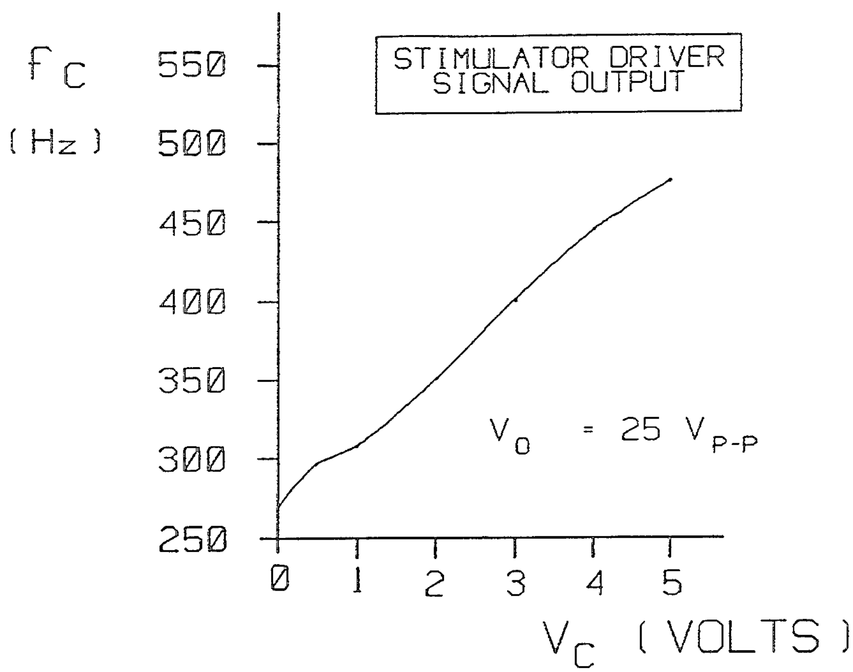


Figure 45. Stimulator Driver Response - High Level Input

stimulator drive signal could be altered. In Figure 44, tactile information is shown as an increasing amplitude signal at a constant frequency. Once a given level of magnitude is reached, it is maintained while the frequency of vibration is increased over the range of increasing force. The response of the operator and the actual required drive levels of the stimulator may dictate different levels, slopes, or even more complex response (log, etc.). The linear pattern shown in Figure 46 was used for preliminary investigations.

A stimulator driver which provides these capabilities was designed and built. It's conceptual design is shown in Figure 47. As with the sensors, once a particular stimulator and response pattern has been selected based on development tests, a simpler device may be designed. Two drivers were constructed for use in Phase I experiments.

2.2.3.2 **System Functional Analysis.** General operation of the system consists of sensing, computation/calculation, and control functions. Information is collected from various sensors and used to calculate control signals to cause the system to respond as desired. The operator provides the initial input of desired system response and modifies/updates this based on feedback information received indicating the actual response of the system.

Signals from the position and force/tactile sensors are first converted to standard analog voltage levels by special purpose signal conditioning circuits. These uniform analog voltages are sent to the PC/AT through a multichannel Analog to Digital (A/D) converter located on a card within the PC. Under software control they are sampled and converted to a digital value which the computer can then use in computations for position control or for force/tactile feedback information.

The PC provides required drive signals to the slave motor controller in response to the desired position signals obtained from the master controller glove. These signals drive the slave motors, in an open-loop manner, to a position determined only by the position of the master glove. Operation in this portion of the loop is independent of any resistance encountered by the slave. That is, as long as the maximum capability of the slave motors is not exceeded, the system will drive the slave to the commanded position without regard as to whether or not an object has been met. Because the absolute position of an object to be grasped is not precisely known, this method alone is not adequate to allow the system to function correctly. Additional control information must be provided to the operator in the form of feedback. In this system this feedback consists of vibrotactile stimulation.

The PC calculates the level of stimulation required from information obtained from the force/tactile sensors. These levels are converted to standard range analog voltages by a multi-channel Digital to Analog (D/A) converter located on a card within the PC.

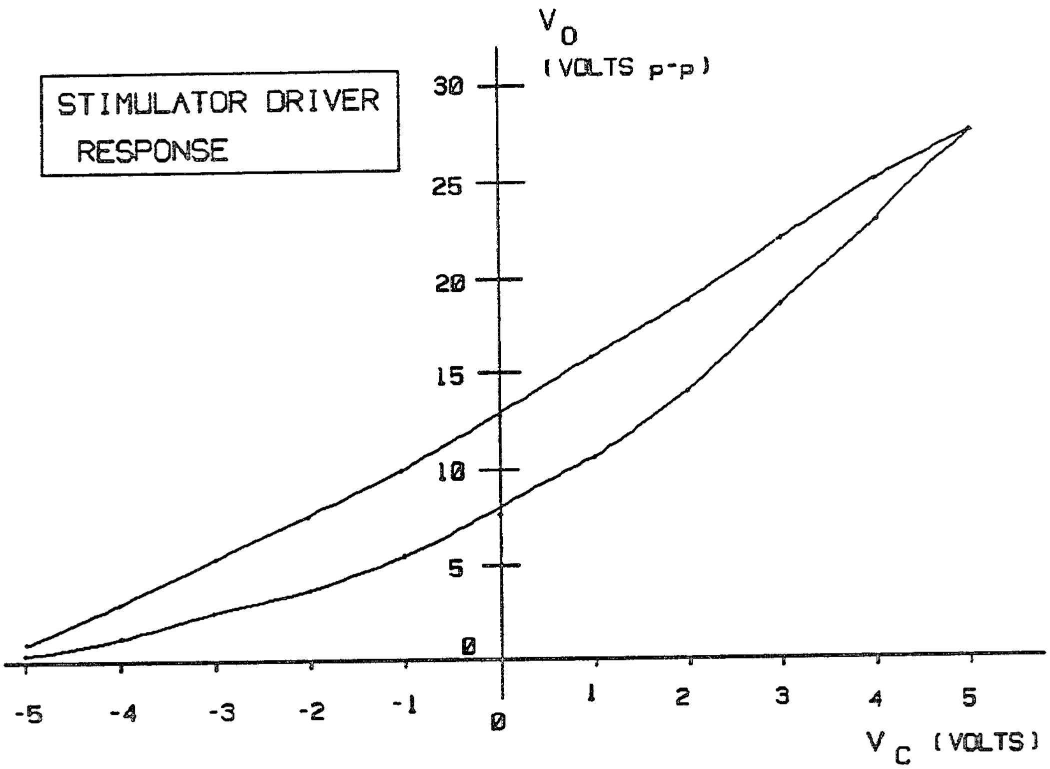


Figure 46. Stimulator Driver Response (Test Configuration)

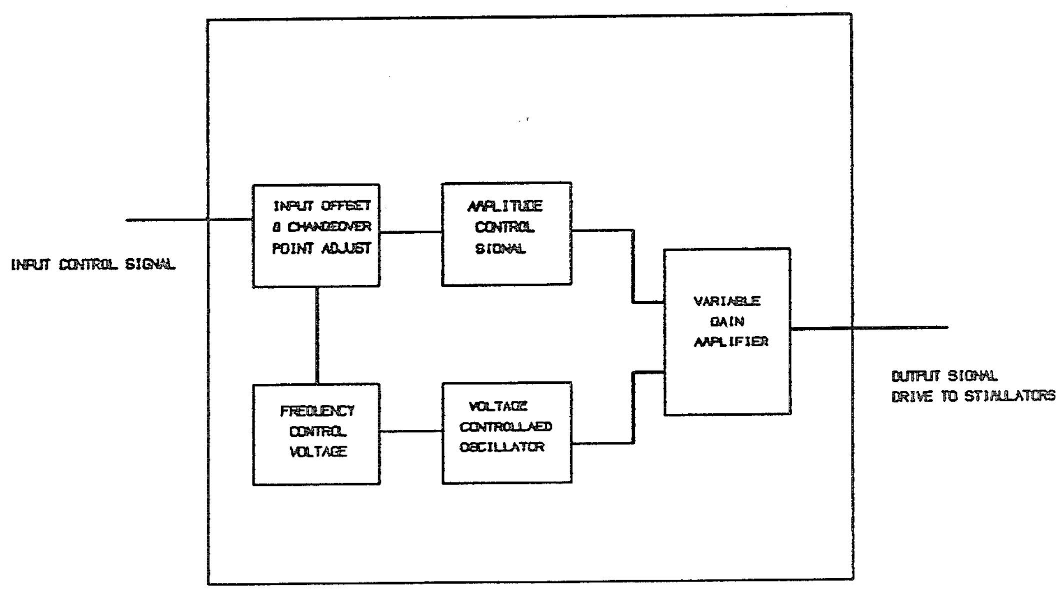


Figure 47. Stimulator Driver Concept - General Design

These analog voltages are applied to a stimulator driver which produces sinusoid voltages which, in turn, are used to drive the piezoelectric stimulators. The magnitude of the control voltages from the D/A outputs determine the magnitude and frequency of the perceived vibration by the operator.

2.2.3.3 Architecture Design Alternatives

A number of approaches and design alternatives were considered in determining the final system configuration and composition.

It is best to maintain separation of tasks within the system to the maximum extent possible. This implies that, as previously stated, signal conditioning and stimulator functions should take place in individual units rather than within the PC/AT. The primary reason is that, no matter how fast a computer runs, someone can - and will - overload it with tasks. Design of real time operating software is a complex and delicate job and is very difficult if not done on a custom designed machine. The convenience of higher level languages, by its very nature, increases response time and decreases efficiency. While the use of the PC/AT as a central processor allows great flexibility, the tasks it must perform should be kept to a minimum.

A second advantage to the distributed approach is that compatibility with other systems is increased because interfaces to the processor are kept to standard levels. Also a minimum of special purpose software would be required to connect, for example, the master glove to a different slave and control system. A application to a different slave would then be facilitated.

In the interest of maintaining simplicity, test tasks should be conducted with the minimum additional system sections. In other words, gripping tests should not involve the use of a robot arm and wrist system. These would only add unaccounted errors to the performance and make comparisons of similar tests run on other systems difficult at best. Of course, eventual use of the OTCG system will involve use of many degree of freedom systems along with a much more complex slave hand; however, there is no need to conduct preliminary demonstrations and tests with these unnecessary complications.

One of the first and most basic decisions addressed was to determine how much of the signal processing should take place within the PC/AT and how much should be accomplished by special purpose hardware. In a centralized processing approach, signals from the sensors would be directly connected to the A/D inputs of the computer. Likewise the D/A outputs (or an amplified copy) would provide the stimulator drive signals directly to the piezoelectric stimulators. This method has the advantage of relatively straightforward hardware of minimum complexity. However, a major drawback is the heavy loading of the processor's operating time.

As an alternative to central signal processing, the signal processing may be distributed. That is, a portion of the required computations and transformations may take place in special purpose hardware of unique design. This design offers greater flexibility in that the central processor is less likely to be duty cycle limited even if the actual type of sensors is changed. Likewise, a specially designed driver circuit can provide the actual drive signals to the piezoelectric vibrators in response to a variable magnitude analog signal from the PC/ATs D/A converter.

Another set of alternatives to be considered involve the presentation of the force/tactile information to the operator. Changes in force could be displayed to the operator in the form of amplitude changes in the vibration; as frequency changes; or as some combination of these. One possibility, as noted earlier, is to use both amplitude and frequency changes in vibration to convey both the lighter tactile and stronger force ranges to the operator. As shown in Figures 44 and 45, a stimulator driver was designed which can provide variations in both amplitude and frequency as a function of a single control input voltage.

2.2.3.4 Final architecture

The final architecture selected for the system includes a PC/AT type computer with internal A/D and D/A capability, multichannel stimulator drivers to convert an analog drive signal into a pattern of controlled amplitude, fixed frequency drive signals for vibro-tactile stimulators, and signal conditioners to convert the force/tactile sensor outputs into standard range analog signals for input to the A/D converter channels. The optical position sensors produce an output directly compatible with the A/D input ranges.

2.2.4 Software Development

The ultimate control, monitoring, and driver system and interfaces will require extensive software design and development. This software will define coordinate transformations, component system dynamics and control algorithms and define the mapping between tactile sensors and interfaces between components. The software will ultimately be provided to collect test data and assist with reconfiguring for various tests. During the glove system development process this software must be designed for easy modification to facilitate system design and engineering modifications. During Phase I software development requirements were minimal. Software was developed to complete the tests and demonstrations planned. This consisted only of modifications to existing WCSAR programs controlling the test bed equipment. The full complement of software required will be completed in Phase II.

2.2.4.1 Phase I Software Requirements

For Phase I development and testing, very little special purpose software was required. This was due in large part to the decision to maintain a distributed computation system. The role of the central computer was kept to a minimum and most specialized functions - for example, the variation of both stimulator amplitude and frequency - were controlled by unique hardware design. The PC/AT computer was used to control the A/D and D/A signal conversions; however it was not required to perform the actual input-output state transformations. This prevented any possible of over tasking the central processor with a resulting duty cycle and response problem.

2.2.4.2 Software Approach

In the design of the system to be tested in Phase II, it was decided to continue the distributed computation approach. This has the advantage of allowing flexibility in the detailed implementation of various types of stimulator input-output transformations, various position sensing schemes, and different control signal responses without concerning the balance of response time and duty cycle. Signal processing which is unique to a particular stimulator type or position sensing method may be accomplished by special purpose hardware with interfering in the central processor's role in overall control.

2.2.4.3 Software Design and Development

Software design will be conducted in a systematic top down manner. Common service functions, such as the A/D and D/A conversion, will utilize readily available standard routines. Special purpose software, written in "C", will be created to control the higher level functions at the overall system executive level.

Development of the software will be modular. That is, as much as possible separate functions will be isolated. This strategy follows in line with the distributed computation approach. For example, one module will transform standard range inputs obtained from the A/D converted position signals into a standard range of values to be used for the control of slave position. Another module will transform these standard values into actual control command values which will then be changed into analog output signals (by the D/A converter) which will drive the slave motor controller. By separating these functions, it is possible to replace, for example, the motor drive controller while altering only one module.

2.2.5 Interfaces

Due to the large number of sensors on the robot hand and stimulators on the control glove, the interfaces to the system

control electronics need to be very carefully designed. Sensor outputs need to be encoded and multiplexed. Conversely power transmission to the stimulators should be supplied through a multiplexed D/A converter structure using, for example, a in n : n decoder chip and voltage multiplier chips. The system electronics and software then will need to be designed to receive and generate multiplexed data streams. The appropriate interface will be defined, and their designs optimized. Requirements levied in other system elements will be defined for their inclusion in the design of those elements.

2.2.5.1 Sensor encode/multiplex structure

The position sensors developed by Orbitec produce a high level output (on the order of several volts). For this reason no local preamplification is required to prevent interference from random electrical noise. The sensor signals may be routed directly to the computer A/D inputs. A power signal for the optical source and an excitation signal for the detector are required for each sensor. However, the power signal is of very small magnitude (approximately 10-30 milliamps) and may be common for all of an array of sensors. In the same way the excitation signal may be common to all of the array of sensors, and may, in fact, be common with the power signal for the optical source. A separate signal line is required from each sensor to return the position signal.

If the power and excitation signals are provided in common to all of an array on n sensors, a total of n + 2 wires will be required to connect the array to the computer. If is desired to reduce power consumption, the optical source power and the detector excitation signals may be pulsed. The output signals from each sensor could be connected in common since only one would be powered at a time. Thus and array of m x m sensors would require a minimum of 2m + 1 wires. This also has the advantage of requiring only a single A/D converter in the central computer because there would be only one signal to read at any one time.

The same general principles apply to the force sensors located on the slave unit. The number of wires and the need (or lack of it) for preamplification would be determined by the particular type of sensor used. If a low level output device, such as strain gages, is selected, preamplifier would be required in close proximity to the slave to eliminate the effects of electrical noise. In general, however, such sensors would require a power source (2 wires) and a single wire to carry back the information signal. By pulse selecting the particular sensor within an array, the number of wires could be reduced in the same as described for the position sensors.

Power requirements for sensors are very small and thus # 32 stranded wire may be used to make connections between the sensors and the computer A/D inputs. This allows the glove wiring to reduced to a small mass and non-interfering size.

2.2.5.2 Stimulator multiplex/decode structure

Stimulators are driven by a relatively high level (volts) signal and are thus not greatly effected by noise. They require one wire for power and one for power return. However, the power return may be common for a number of stimulators. Pulsing power to an array of stimulators is not, in general, as appealing as it is for sensors. The stimulators need to be driven at all times instead only requiring sampling, thus the m x m array described for position sensors would not simplify the system.

As for the position sensors, the current requirements are extremely low and # 32 wire may be again used to reduce the bulk and mass of the wiring.

2.2.5.3 Requirements levied on other elements

By using the distributed computation approach, and requirements applied to the computer of any connected system may be kept to a minimum. All input/output signals are converted to standard ranges by specialized hardware (signal conditioners and stimulator drivers) and can thus be applied to any general purpose computer with analog I/O capability. Power requirements are minimal.

If arrays of sensors and stimulators are used, the host computer must be able to control sample times. This may impose limits to any interrupt driver signals within the host system. The time required to process the array of I/O signals may increase the duty cycle of the host machine, but should not overload a properly designed system.

2.2.6 Integrated total system design

Based on the evaluation of available components and subsystems as well as the results of the component research and testing conducted, the preliminary design of system components was completed. The areas of glove and supporting structure (exoskeleton), position sensors, stimulators, and control/computation architecture were examined to determine a total system design for a laboratory prototype system for Phase II development.

The design chosen for the mechanical portion consists of a close fitting glove which serves to hold the vibro-stimulators in close contact with the operators fingers, the linked exoskeleton with optical rotational position sensors as an integral part of the joints, and the mechanical hand connection device for attaching to an arm-wrist system. (see Figures 33, 4, 34, 35, 36).

Unique signal conditioners and stimulator drivers will be used to convert multiplexed arrays of the optical position sensors and

electromechanical vibrators into a small number of standard range interface signals for connection to the central control computer. This computer, a PC/AT, will contain integral A/D and D/A converter boards, which will accept and provide standard range interface signals for the glove controller as well as any end effectors and force/tactile sensors which may be tested with the system. The overall architecture of the system is shown in Figure 41.

A review was held and minor alterations incorporated to provide an established baseline design for Phase II investigations. This design incorporates all of the results of Phase I investigations. It provides for a low-risk, adaptable system which may be integrated with a variety of different end effectors and controllers to conduct advanced performance testing of the controller glove concept.

2.3 Demonstration and testing

The objective of the demonstration and testing is provide adequate information and experience to identify problem areas, expose potential "showstoppers", and to demonstrate a basic level of feasibility. The demonstrations and tests have also provided insight into future modifications and developments of the OTCG. Specific components that will be demonstrated and tested include the stimulator devices, position control, and sensor response.

Prototypes of the stimulator devices have allowed sampling of various technological approaches to vibratory input to the skin and understanding of basic stimulation issues and considerations. Key issues include the level of dynamic response delivered for various wave forms and amplitudes, the modes of operator interpretation of the vibratory stimulus, the effect of mechanical resistance, and the mounting configuration of the stimulator devices.

A prototype of the position control was developed for a single digit with four degrees of freedom. Range of motion and dexterity, are important considerations with respect to anthropomorphic similarity. Comfort, simple ingress/egress, versatility to accommodate various hand sizes, compactness, light weight, and potential for accuracy were key considerations in the development of the prototype demonstration of the position monitoring device.

Sensors prototypes were investigated as a complimentary effort supported by ORBITEC and the State of Wisconsin. Prototyping of sensors began prior to this Phase I award and have provided insight into the type of sensor data with which the OTCG must interface. These sensors also provided input in the prototype devices to drive stimulator inputs.

2.3.1 Stimulators

Through the Phase 1 effort, ORBITEC has strived to conduct preliminary and intermediate tests of ideas and components to

assist in the guidance of the overall system design. Such demonstrations and testing involve development of laboratory prototypes and development of test apparatus and testing procedures. Support was supplied to ORBITEC from the State of Wisconsin and the Wisconsin Center for Space Automation and Robotics which maintains a large robotics laboratory with mechanical design, electrical design and human factors evaluation expertise. This demonstration and testing was concentrated in areas of stimulation and position control. Initial demonstration and testing was conducted in the areas of sensors and system integration. Each of these will be described below.

The demonstration and testing of stimulators encompass three major areas:

1) assembly and prototyping of electromechanical and piezoelectric stimulator elements for lab testing,

2) development of stimulator drivers for variance of both frequency and amplitude, and

3) vibro-tactile human performance testing.

Both electromechanical and piezoelectric stimulator elements were prototyped in the laboratory and driven by prototype stimulator drivers. A piezoelectric element mounted on a semi rigid rubber washer was selected for further evaluation in vibro-tactile human performance testing. Each of these areas will be discussed in more detail below.

2.3.1.1 Demonstration and Testing of Stimulator Devices

Both electromechanical and piezoelectric stimulators were developed in the laboratory. All prototypes were developed as extrapolations from off-the-shelf hardware components sold as acoustic buzzers. For the selected electromechanical and piezoelectric stimulator configurations, subjects were tested and trained on the prototype lab sensors via a very simple resolution definition test. The test setup was configured such that the inputs to the driver varied from -5 volts to 5 volts over 12 different steps. Each subject was asked to identify the first level at which he/she could feel the input vibration. This minimal level was then defined as the low level vibration for further testing. The first round of testing and training continued with a demonstration of what a low, medium and high input vibration was. Once the subject felt comfortable in acknowledging the difference between the low, medium and high levels, a series of random samples were given to the subject for which the subject had to interpret the signal and identify which of the three levels was being input.

The second series of tests increased the resolution from three to four now having a low, low-medium, high-medium and high levels

of vibration. Similar demonstration and testing were done for the four-level test.

The electromechanical laboratory stimulator was derived from an electrical magnetic induction coil from a star micronics acoustic buzzer (Shown in Figure 48). The coil was used with a 250 Hz sign wave current to change the magnetic field induce a 0.8 cm diaphragm to vibrate. This stimulator gave efficient stimulation at voltage inputs (i.e. from a -5 volts to approximately -2 volts) lower than other prototypes tested. However, as the input amplitude was increased, the stimulator began to emanate acoustic noise more than additional laboratory output. Initial subject training on the prototype stimulator showed that no additional vibration was detected beyond the fourth level of stimulation. This device would require redesign such that resident frequency of the diaphragm matched the 250-400 Hz vibration frequency desired.

This solenoid application, however, appears to be fairly efficient at low voltage levels. Previous experience of an ORBITEC associate has shown that a solenoid coil with an embedded stimulator pin operators extremely efficient as a stimulator. Six levels of stimulation resolution have been observed with little or no training of the subject.

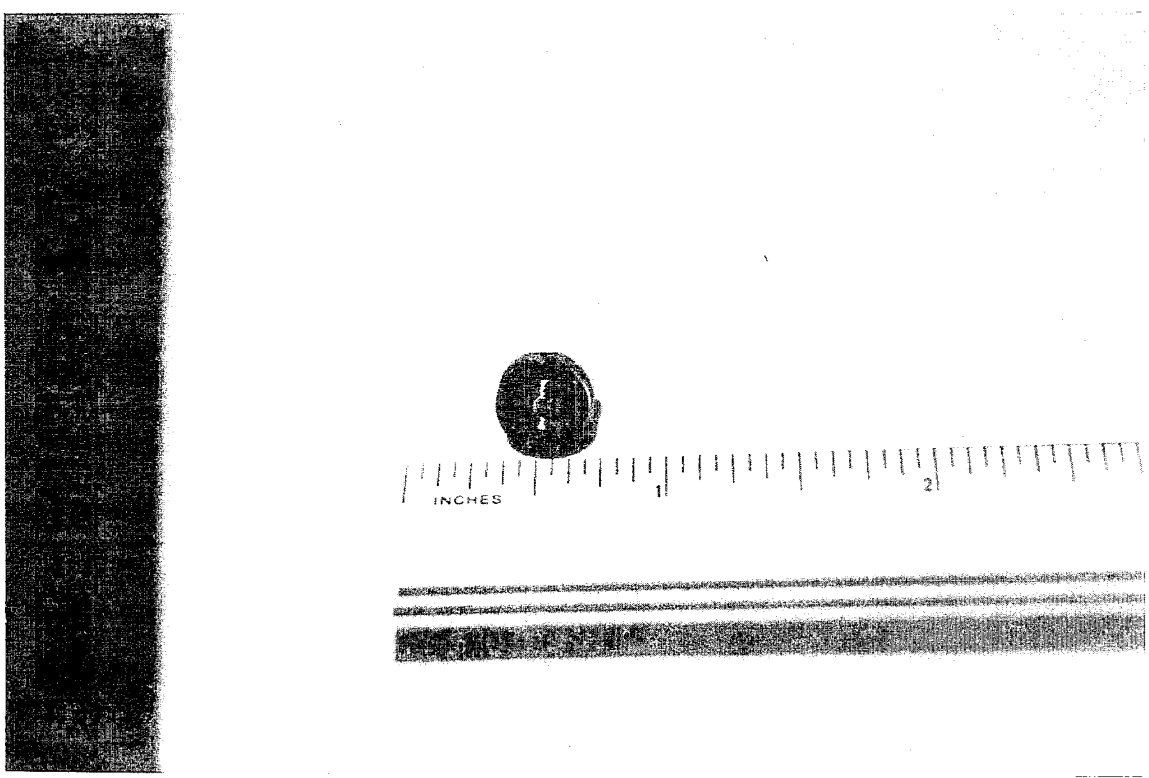


Figure 48. Sample Electromechanical Stimulator Solenoid

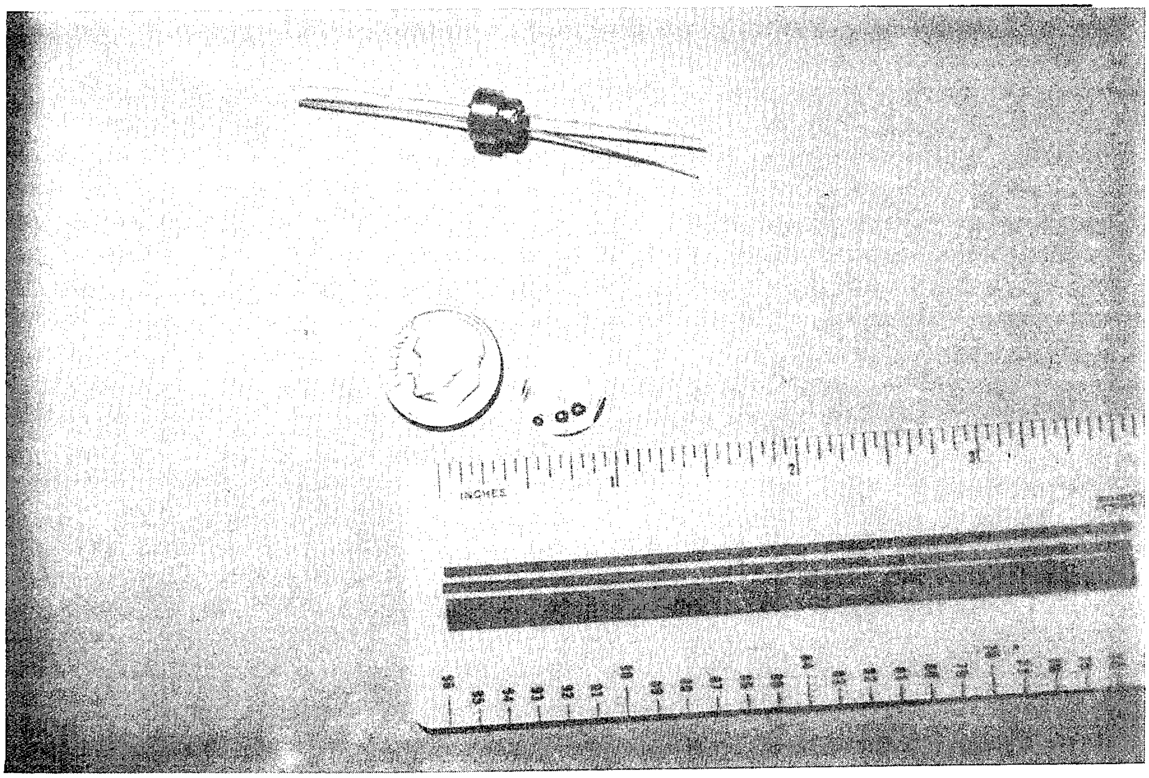


Figure 49. Prototype Piezoelectric Stimulator Element

Of all the piezoelectric devices investigated, the small circular sub-plate with piezoelectric crystal mounted was chosen as the base device for further evaluation as it provided the greatest laboratory response (Pictured in Figure 49). The off-the-shelf piezoelectric crystals substrates did not appear to have great precision in their manufacturing. The crystal application was in most cases not centered on the substrate. This, however, did not seem to have a direct correlation on the level of vibration for a given input signal. Crystals that were off-centered sometimes vibrated as well or better than crystals than were centered with respect to the substrate. The quality of the crystal is likely to have more of an effect than the preciseness of the crystal location of the substrate. There was a wide variance in vibration and acoustic output of these devices given a constant standard input signal.

Several different mounting approaches were tested and were shown in Figure 7. These mountings ranged from mounting rigidity and attachment approach. Over 15 different mounting configurations were sampled; the most unique types are as follows:

1. Glove mounted no cover - stimulator device directly attached to the inside of the finger of the fitted glove with no separation between the piezoceramic disk and the inserted human fingertip. (freely supported stimulator)

2. Glove mounted with nylon cover - stimulator device directly attached to the inside of the finger of the fitted glove with an nylon mesh cover between the stimulator and the finger. (freely supported stimulator)

3. Oval pad sandwich with top layered trimmed - stimulator device mounted on a foam disk with rigidity close to that of firm human tissue; a second foam disk contoured to the shape of the finger was placed on top of the stimulator and bottom disk. (large diameter support with little/no resonant frequency change)

4. Oval pad sandwiched with sharp protrusion cemented onto crystal - same as #3 with a sharp elliptical protrusion attached to the center of the stimulator device such that the elliptical cone provided the major physical contact to the fingertip. (vibratory stimulation with lever arm)

5. Oval pad sandwiched with rounded protrusion cemented to crystal - same as #4 with a rounded elliptical protrusion. (vibratory stimulation with lever arm)

6a. Small O-ring back - A rubber O-ring with diameter smaller than the outside diameter of the stimulator disk was mounted to the back of the stimulator device. (small diameter support, little resonant frequency change)

6b. Large O-ring back - same as #5 with an O-ring of inside diameter equal to the outside diameter of the stimulator device. (large diameter support, little resonant frequency change)

7. Sponge back - stimulator disk mounted to a flat, very light sponge material (continuous, slight lowering of resonant frequency)

8. Foam back - stimulator disk mounted to a flat, skin-like foam (continuous support, lower resonant frequency)

9. Small rigid washer back - steel washer with an inside diameter smaller than the outside diameter of the stimulator disk (small diameter support and lower resonant frequency)

10. Large rigid washer back - same as #9 with a steel washer of inside diameter equal to the outside diameter of the stimulator disk (large diameter support and lower resonant frequency)

11. Plastic washer back - same as #10 with a plastic, lighter washer (large diameter support and lower resonant frequency)

12. Hard rubber back washer - (large diameter support and lower resonant frequency)

13. Soft rubber back - (large diameter support and lower resonant frequency)

14. Donut foam back - same as #3 without contoured foam top

15. Cut piezo crystal strip - deformed resonant crystal

From the tests of these various configurations, it was apparent that the glove mounted without the nylon cover was the best method of mounting the vibratory stimulators. Other conclusions include that a semi-rigid or soft rubber back with an inside diameter equivalent or just small than the outside diameter of the metal substrate produced the best vibratory stimulus. Soft foam backing or any backing which touched the middle of the substrate tended to damp the vibration out. The cut strip did not function at all; the resonant properties of the stimulator device is destroyed.

The piezoelectric crystal device used in these tests has the crystals aligned the width direction of the substrate. When the crystal is electrically excited with a positive voltage, the crystals elongate causing a deflection of the circular substrate. The crystal is only mounted in the center 0.8 of a millimeter of the 1.2 centimeter diameter substrate. Thus, the substrate has a resident snapping up and down as the center of the crystal is deformed, elongated and contracted with the crystal elongation and contraction. A recommendation to improve the vibration characteristics of this device is the calculate size changes such that the a-resident frequency between 250-400 hertz is reached. Also applying the piezoelectric crystal to both sides of the substrate and charging them oppositely may provide additional elongation and contraction of the center of the substrate thereby causing a dynamic response. Attempts were made and are being perused to contact vendors of these piezoelectric crystal elements. No vendors were found in the United States. All vendors identified are located in Japan, China and the Philippines. Initial contacts were made to these vendors. No response has been received to date. ORBITEC is interested in pursuing an original prototype design of these substrates and piezoelectric crystal applications to develop a vibratory stimulator resident at the 250-400 hertz frequency range.

Initial testing in the laboratory of subjects with the piezoelectric crystal stimulators in the glove mounted configuration were conducted in the three and four resolution tests. With minimal or no training all subjects could resolve levels of vibration to both the three and four degrees. The stimulation response was not felt until level two or three was reached however a continuous and increasing laboratory stimulus was felt from that low level to the highest dynamic output. Much less acoustic information is generated by this advice as opposed to the prototype electromechanical stimulator.

From the initial testing and training of the vibrational stimulus, it is apparent that demonstration of the vibration stimulus to subjects is very important for their understanding of what the vibrational stimulus corresponds to. After stimulation tests were conducted, subjects could much more easily interpret the response. In other words, the more experience the subject had with the laboratory response, the quicker he could resolve the stimulus into the appropriate level of resolution. If the same tests were carried out measuring the response time of the subject, this learning curve may become very apparent.

2.3.1.2 Stimulator Driver Demonstration and Testing

A demonstration stimulator driver was designed and fabricated using wire wrap techniques. This device was designed to drive the piezoelectric vibrating stimulators in response to and input control signal. The input signal may vary over a five bolt range beginning as low as -5 and as high as zero volts. Nominally the input signal range is set to -2.5 to +2.5 volts.

The input signal causes the output to vary from approximately 160 Hz to 1 KHz in frequency at an amplitude if +/- 4 volts. A voltage controlled oscillator produces a triangular wave form which is converted to a sine wave by a resistor-diode network and then amplified to produce the output signal to drive the stimulator. The output signal may be delivered to two stimulators.

The attached drawing (8942-001) shows the circuit. Table 12 gives the input/output connector pinout and Figure 50 shows the location of the controls and input/output connectors.

A dual channel stimulator driver was designed and constructed as shown in the attached schematic diagram. The device is designed to operate from standard 120 VAC, 60 Hz power and to drive two piezo electric vibrator stimulators. A control signal of -2.5 to +2.5 volts is used by each channel to control both the frequency and magnitude of the output signal. The attached drawing (8942-002) shows the circuit.

The stimulator driver was designed using LM324 op amps as the only active devices other than the voltage regulators. A block diagram is shown in Figure 51. It consists of two identical circuit halves (one for each channel) and a common power supply. Trim pot R2 is used to adjust the acceptable control signal input range. This signal may cover a 5.0 volt range beginning as low as -5 or a great as 0 volts. Nominally, the range is set to accept signals from -2.5 to +2.5 volts. As the control signal increases from the minimum, the output signal increases from near zero to a maximum of approximately +/- 13.5 volts, reaching this maximum at an input signal level called the changeover point. Once the input signal reaches the changeover point the output signal is maintained at this maximum magnitude and increases in frequency from

approximately 100 Hz to 1 KHz. The input signal level corresponding to this changeover point is nominally set to approximately 20% of it maximum range and may be adjusted with trim pot R18.

The output signal is generated by a voltage controlled oscillator which produces a triangular shaped waveform. This is converted to a sine wave by a resistor-diode network. Transistor Q2 then delivers a portion of this signal to amplifier U1C which produces to output signal to drive the piezoelectric stimulator with a sine wave signal. The maximum amplitude of the output signal may be limited with trim pot R46.

The power supply circuit produces plus and minus 15 volts to power both channels of the driver. It uses two solid state three terminal regulators.

Figure 50 shows the location of control pots and input/output connectors and Table 12 gives the input and output connector pinouts.

TABLE 12. CONNECTOR PIN ASSIGNMENT

CONNECTOR - 9 pin female D-Connector

PIN	SIGNAL
3	Channel 1 output drive
5	Channel 2 output drive
7	Signal ground
9	Signal ground

CONNECTOR - 15 pin male D-Connector

PIN	SIGNAL
3	Channel 1 input signal
5	Channel 2 input signal
10	Signal ground
12	Signal ground

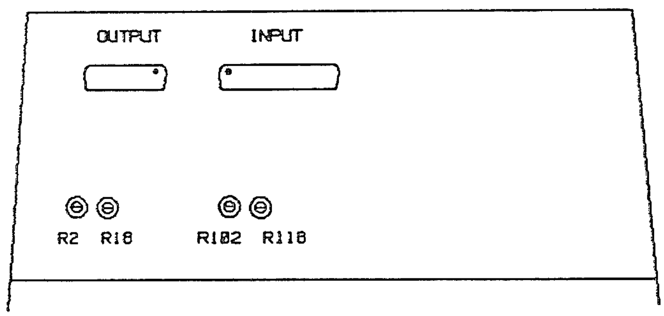


Figure 50. Front Panel of Prototype Stimulator Driver.

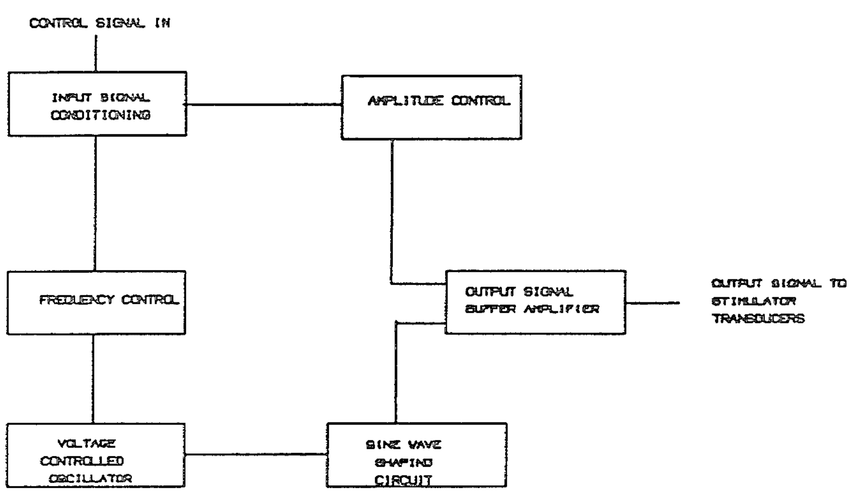


Figure 51 Block Diagram of the Prototype Stimulator Driver

Vibro-tactile Testing Procedure

Future experiments have been designed to test the effectiveness of vibro-tactile feedback, as compared to force feedback and visual feedback. The vibro-tactile feedback will be provided by vibro-tactile elements of the types described in Section 2.1.1 in various vibrational modes that were also discussed in Section 2.1.1. The experiment will consist of tracking tasks which were performed on a single degree-of-freedom gripper mechanism.

Dexterous manipulation and grasping in telerobotic systems depends on the integration of high-performance sensors, displays, actuators and controls into systems in which careful consideration has been given to human perception and tolerance. The ultimate goal driving the design of telerobotic systems has been to provide the operator with information which comes as close as possible to duplicating the conditions present at the slave manipulator. Several types of displays will be developed to test various stimulus modes and approaches and alternative hardware configurations and be used to relay force and/or tactile information to a teleoperator. It is important to study the effects of each of these types of display on the human operator, and to develop a fundamental understanding of performance issues involved.

These tests will provide an initial outlook at the various human performance levels at the different frequency bandwidths to give a general portrait of performance. Than various forms of vibrational and visual inputs will be sampled. Degraded vision, multi-mode vibrational input, and combined vibro-tactile/force reflection tests are priorities. These tests will be conducted during Phase II.

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3.0 RESULTS AND FINDINGS

This section provides a brief summary of the major results of the Phase I SBIR effort. A general summary, conclusions, and recommendations are provided below.

3.1 Summary

This Final Report discusses the Phase I SBIR research results for an innovative system for telerobotic control of dexterous end-effectors. The system, known as the ORBITEC Telerobotic Control Glove (OTCG), provides a human operator control of position and forces applied by a slave telerobot using the feedback of force and tactile information from the slave to the operator. The functional mode of feedback of the OTCG allows for a simple, low-cost, light-weight, and versatile device that may be integrated and used to control position and forces of various dexterous manipulators/end-effectors. Tactile and force/torque information may be displayed to the human operator via vibratory displays located on the hands of the operator. This device offers an effective and efficient alternative to force reflection techniques to avoid inherent large mass/power designs and operational instabilities. Also, the OTCG may be used to compliment force reflective systems in an existing dexterous master controller or an arm/wrist master controller to enhance operator performance due to increases sensory information display. The purpose of the Phase I effort was to establish technical feasibility of the OTCG approach.

During the Phase I SBIR effort, various key master controller glove components were assessed, researched, designed, prototyped, and tested by ORBITEC. Preliminary requirements and design for a prototype glove system were established. Proof of concept feasibility was accomplished through systematic testing of the key components and overall concept analysis and definition.

The results of this Phase I effort provide insight to a point design of the OTCG, which will allow human telerobotic control of a wide variety of robotic end-effectors with appropriate feedback mechanisms. This design also my be easily integrated with existing arm/wrist controllers. The Phase II effort will lead to development of a complete controller system which would be used to control any of several robotic hands available today. The OTCG will also be able to integrate into several of the commercial and laboratory models of arm/wrist controllers to enhance the control of end-effectors ranging from dexterous capability to simple parallel jaw capability.

The primary application for OTCG technology is for assured ability to service, maintain and operate military aircraft in hazardous environments. Those environments may include the

presence of toxic fuels, chemicals, biological agents and nuclear radiation. Other applications include servicing of Army, Navy, and Marine vehicles and equipment, munitions handling, and some combat applications. It could also applied widely in the subsea and nuclear industries and for servicing satellites in space for the USAF, SDIO and/or NASA. In addition, there is enormous potential for commercial terrestrial applications.

Summary of Stimulator Results and Findings

Force and touch information is to be conveyed to the operator by means of vibration stimulators located in the master control glove. Each tactile/force sensor on the slave end effector will be directly mapped to a corresponding stimulator in the glove. Tactile (low range), normal and shear force (high range), and torque data will be presented via a single stimulator via different stimulation modes.

Developments key to the stimulators include: (1) choice of appropriate stimulator technology that can provide adequate resolution and dynamic response; (2) the location and configurations of the stimulator devices in the glove; (3) mode of stimulation feedback to accommodate tactile, normal force, shear force, and torque displays; (4) configuration of the stimulators to adequately display torque information; (5) provision of a standard interface such that any sensor can be configured to activate stimulator response.

Stimulators considered for this function must be small in size, require only relatively low operating voltages for safety reasons, and provide localized stimulation. Prolonged use of the device must not produce reduced sensitivity or operator fatigue. For greatest sensitivity of the operator, the stimulator should operate in the 100 to 1000 Hz range with an optimal response in the 250 to 400 Hz range. Two classes of stimulators were investigated during this effort: electromechanical and piezoelectric.

The preferred alternative electromechanical stimulation concept contains a single solenoid per stimulator. Each solenoid has a diameter of 8 mm such that a 3x3 array of stimulators may be possible in a square inch which may fit on the fingertip. Arrays of various sizes may be developed for other surface areas of the hand or other parts of the body. Additional developments are required to maximize the solenoid activation efficiency, and mounting of the arrays. This concept has extremely high potential to create better dynamic responses in more dense resolution arrays than other alternatives which will allow more versatility in providing a wider range of stimulation and stimulation modes.

Over 16 configurations of the piezoelectric stimulator devices were assembled for preliminary response testing. All of these prototype configurations used the small piezoelectric ceramic disks

with alternative mounts. The most efficient mounting configurations for the piezoelectric stimulators were the fitted glove and the semi-rigid washer backed configurations. Each attached the stimulator disk at the perimeter and allowed full deflection of the resonator against the finger.

Initial stimulator prototypes driven in the amplitude mode only have shown that four to six levels of resolutions can be perceived by the finger with minimal or no training. Several other parameters must be investigated as to their effect on the gradient response of the perceived vibratory input levels. The most critical parameters include:

- Vibratory amplitude
- Vibration frequency
- Area of vibration
- Pulsed frequency of vibratory stimulus
- Mechanical impedance between the skin and the stimulator.

Many of the single variable gradient responses have been investigated in the past. From the existing literature and from experience with the vibratory stimulation, ORBITEC believes that a combination of these parameters will provide the best operator interpretation of the sensor data. Two examples of combining the various parameters are demonstrated below. Much more complicated schemes are possible; but have not been investigated under the scope of this contract.

Sensors

Research and development of sensors, although not directly related to the OTCG for display of information, provided insight into the types of information to be displayed and provided interfacing testing apparatus for the OTCG. ORBITEC has reviewed several state-of-the-art sensor technologies available on the market and being developed. We have concentrated our own developments on the Multi-degree-of-freedom Robotic End-effector Sensor (MRES) and potential evolutions, and the piezoresistive flexible membrane sensors. Both sensors provide a good response in the tactile range.

ORBITEC personnel have developed flexible piezoresistive sensors which are extremely sensitive in the tactile range of touch. The sensor material is applied to a thin flexible substrate. The response of these sensors which were tested via a controlled rate compressive test configuration revealed very high sensitivity in the tactile regime. The sensors consist of a molybdenum-impregnated vinyl which is layered against a silvered conductor. The sensitivity and hysteresis characteristics can be modified by the vinyl mix. By modifying both the composition and the configuration of the composite materials of the sensor, different force ranges and sensitivities have been demonstrated.

This sensor has good potential with the following recommended modifications:

- A more flexible substrate rigidized around the element
- Modified conductive mixture for less hysteresis
- More consistent mounting technique.

These sensors should be pursued upon definition of the test slave device such that a specific design of the substrate and size of the sensing elements may be accomplished. No further effort is recommended until the slave application is defined.

The Multiple-degree Robotic End-effector Sensors (MRES) has two configurations both consisting of compliant members containing several transducer elements. One configuration would be attached to the tips of a robot dexterous end-effector finger and would resolve three orthogonal forces and a torque. The second configuration would attach along the sides of the end-effector fingers to resolve normal and shear components along a surface. The MRES functions to detect contact, applied force, surface shape, slippage, and other characteristics of a grasped object. The sensing capability of the robot hand would be similar to the sensing ability of human fingers measuring forces on the order of 0.1 gram with high incremental resolution. Separate independent force, tactile, and torque sensors could be replaced by the MRES.

Position control

Assuming an adequate sensor is available, the problem that remains is to integrate that sensor into a device that: (1) comfortably attaches to the operator's hand and fingers; and (2) reliably and accurately tracks finger movements. The entire device must then readily integrate with available arm master controllers. A number of solutions to this problem were investigated.

ORBITEC examined the available sensor options that may support position control devices and concluded that none of them completely satisfied the requirements of the OTCG. As a result, a separate research and development program was initiated with support from the State of Wisconsin, Department of Development. Two new concepts for position sensing were developed and explored. One was a new small optical rotational sensor. The other was a unique ultrasonic ranging system. A third sensor type identified needing development was identified (a small sliding flexible optical position sensor), but was not pursued because the system that required it was not ranked highly.

The small optical rotational sensor would use a light source (LED) and a light sensor such as a photodiode. The source and sensor would be separated by two pieces of polaroid plastic with the transmission planes aligned when the light sensor is in the

zero angle position. As the two halves of the sensor are rotated through 90 degrees, the light transmission decreases to zero.

Such a sensor has the potential to be manufactured in an extremely small package - on the order of 1/8 inch diameter and little over 1/8 inch in length. It would require fairly simple signal conditioning and provide sufficient resolution for the desired purpose. This offers a high potential return in the form of a simple, low cost, physically small position sensor.

Six concepts were identified as possible design options for the controller device: (1) Flexible Link, (2) Roller, (3) Cable/Sheathing, (4) A.D. Little/Exos Modification, (5) Mechanical Linkage, and (6) Ultrasonic Ranging. Each concept would integrate with an average (50th percentile) male human hand. The first four of the concepts are intended to be integrated into the fitted glove worn by the operator which would also contain the tactile stimulator array. The fifth is a separate exoskeleton that would be part of a hand bracket that would integrate directly with an arm/wrist master controller.

The sixth concept is very different from the others being an ultrasonic ranging system is similar to an area navigation system. Three receivers are located at known spots in the area of the master hand. A transmitter for ultrasonic pulses is attached to the fingertip of each finger of the glove. A pulse is sent from a finger tip and received at each of the three receivers. By measuring the time the pulse is received at each receiver and comparing this to the time of transmission, the slant range between each receiver and the fingertip may be calculated if the speed of sound is known.

The preferred concept is the mechanical linkage which measures the distance and orientation of the distal finger link with respect to a bracket mounted on the hand. This information is all that is needed to uniquely determine a finger configuration and all joint angles for the slave. The recognition of this is a key finding of this project. Demonstration of this fact and derivation of the required coordinate transformations have been accomplished and documented. These data are important for the new ORBITEC rotational sensor envisioned for this device, as its effective angular range is limited. For integration with an arm/wrist master controller the hand bracket would simply replace the hand grip on that controller.

Concepts are compared with respect to accuracy, repeatability, ease of operator hand mount/attach, sensor requirements and other factors. The "mechanical linkage" concept was selected for the OTCG because it provides a unique combination of attributes not available in any other concept. It can accurately and reliably determine finger configuration, is relatively easy to mount/attach, and is readily integrated with wrist/arm master controllers.

System Design, R&D, Selection, and Testing

The overall system design was developed based on the use of selected components. This design process considered the available test beds and subsystems, the feasibility demonstration requirements of the SBIR, and eventual system development direction. A basic architecture was selected and required special interface devices developed.

The overall OTCG system design includes a fitted glove which maintains the vibratory displays positioned on the operator's hand, a position monitoring linkage which is attached to the fitted glove via a quick disconnect, electrical cabling, and an interface for attachment to arm/wrist controllers. The fitted glove and the position control linkage are attached through a quick disconnect mechanism such that rapid mounting and dismounting can be accomplished. The fitted glove will have its own electronic cabling with quick disconnects at the arm\wrist interface. The position monitoring linkage is rigidly connected to the arm\wrist interface and contains its own electronic cabling.

One of the most important requirements of the OTCG beyond its functional performance is operator comfort. Effectively, two areas of contact are used to attach to the hand. Coupling to the finger is accomplished through a snug fitted finger ring (integrated into the fitted glove) for the distal link of the finger. This ring must conform to an individual operator and will be selected appropriately for the various fitted glove sizes. The Quick disconnect mechanism shall allow for attaching and detaching the fitted glove to the position monitoring linkage.

A prototype of the master hand controller has been built. The prototype was built to verify the feasibility of using such a mechanism as a hand controller and sized accordingly. The primary issues of concern were to verify the methods of attachment to the hand, determine if any restrictions or resistance to finger movements existed, and verify general overall operator comfort. The prototype has proven to be a valuable tool and a series of recommendations are discussed in the following section resulting from testing conducted on the prototype device.

A rigid arm/wrist interface is provided for the OTCG to be attached to a telerobotic arm/wrist controller. This interface is mechanical only; no electrical connections are required although they could be integrated if desired. The interface allows for a solid, rigid interface to the operator such that the operator can impart and receive force and torque information from the arm/wrist controller (assuming the arm/wrist controller is force reflective in nature). It is this interface that provides the OTCG with great versatility as a complimentary capability to existing arm/wrist telerobotic control devices with advance dexterous manipulators.

We have concluded from the demonstration and testing of the position monitoring linkage that this is a viable method to be pursued for obtaining finger joint angle registration. There seems to be sufficient operator comfort when operating the prototype mechanism.

Computer/Control Architecture

General operation of the system consists of sensing, computation/calculation, and control functions. Information is collected from various sensors and used to calculate control signals to cause the system to respond as desired. The operator provides the initial input of desired system response and modifies/updates this based on feedback information received indicating the actual response of the system.

Signals from the position and force/tactile sensors are first converted to standard analog voltage levels by special purpose signal conditioning circuits. These uniform analog voltages are sent to the PC/AT through a multichannel analog to digital (A/D) converter located on a card within the PC. Under software control they are sampled and converted to a digital value which the computer can then use in computations for position control or for force/tactile feedback information.

It is best to maintain separation of tasks within the system to the maximum extent possible. This implies that, as previously stated, signal conditioning and stimulator functions should take place in individual units rather than within the PC/AT. The primary reason is that, no matter how fast a computer runs, someone can - and will - overload it with tasks. A second advantage to the distributed approach is that compatibility with other systems is increased because interfaces to the processor are kept to standard levels. Also a minimum of special purpose software would be required to connect, for example, the master glove to a different slave and control system.

The ultimate control, monitoring, and driver system and interfaces will require extensive software design and development. This software will define coordinate transformations, component system dynamics and control algorithms and define the mapping between tactile sensors and interfaces between components.

In the design of the system to be tested in Phase II, it was decided to continue the distributed computation approach. This has the advantage of allowing flexibility in the detailed implementation of various types of stimulator input-output transformations, various position sensing schemes, and different control signal responses without concerning the balance of response time and duty cycle.

Interfaces

Due to the large number of sensors on the robot hand and stimulators on the control glove, the interfaces to the system control electronics need to be very carefully designed. Sensor outputs need to be encoded and multiplexed. Conversely power transmission to the stimulators should be supplied through a multiplexed D/A converter structure using, for example, a 1 of n decoder chip and voltage multiplier chips. The system electronics and software then will need to be designed to receive and generate multiplexed data streams.

3.2 Conclusions

The conclusions of the OTCG Phase I effort are summarized below:

1. The OTCG concept is technically feasible and should provide a significant new capability for controlling telerobotic dexterous end-effectors in the future.

2. The OTCG has the potential to replace more complex force feedback systems with a simpler device without sacrificing teleoperator performance.

3. The OTCG has the potential of augmenting other force feedback systems to enhance teleoperator performance.

4. OTCG system performance needs to be compared as an alternative and as a complimentary device to other force feedback approaches.

5. The ORBITEC rotation sensor enables a compact, light weight, and versatile position monitoring system to integrate into the OTCG.

6. A unique position of a finger (or thumb) may be determined by knowing the position and orientation of the distal link of the finger relative to a fixed reference point on the hand.

7. Vibratory stimulation is extremely feasible and can be resolved into many levels by the operator with minimal training to orient the operator to understand the meaning of the vibratory stimulation.

8. Different display patterns of tactile stimulators will provide a wide variety of possibilities for feedback and may be optimized for the various information applications (i.e tactile, normal force, shear force, and torque information). An analogy to this variable mode of information display is vision.

9. The size of vibratory stimulators can be reduced such that they can be accommodated on the inside surface a fitted glove. In fact, individual stimulator devices may be integrated into various size arrays of stimulators that will fit on different locations of the body.

10. Piezoelectric acoustic resonators provided reasonable dynamic response with a +/- 15 volt sine wave input. The most significant amplitude vibration was found using a glove or semi-rigid mount.

11. Piezoelectric ceramic resonators may be designed around a vibrational stimulation at the 250 to 400 Hz range to improve the stimulator dynamic response above that experienced from the off-the-shelf acoustic resonators.

12. Overstimulation can occur if the stimulation is not adequately controlled.

13. Auxiliary acoustic, body mounted vibro-tactile or visual displays may enhance performance of the OTCG system

14. The molybdenum based piezoresistive sensors are extremely sensitive and nearly linear in the tactile regime.

15. The Multi-degree-of-freedom robotic end-effector sensor (MRES) has demonstrated a wide range of tactile and force applications with the capability to resolve forces into three orthogonal vectors and a torque about the principle axis.

16. A derivative of the MRES is possible to apply as a thin "skin-like" layer to monitor shear and normal forces.

17. Component technologies of the OTCG represent valuable solutions to broad applications of military robotic and commercial applications.

3.3 Recommendations

The results of this Phase I effort have provided enough insight to the concept feasibility and have provided several alternative developments that support the point design of a OTCG allowing human control of a wide variety of robotic end-effectors with appropriate feedback mechanisms including tactility and forces/torques. This will lead to development of a complete controller system in Phase II which may be used to control several robotic hands including the WCSAR three--fingered hand and the four--fingered MIT/Utah hand.

A flexible interface among sensors, the stimulators and the position control device is planned such that different sensors can be used to provide feedback, and the various degrees of freedom

available in the controller can be remapped to fit the specific end-effector. Also, because of the inherent "glove" design, this controller could be integrated with arm controller devices which can then control and entire dexterous arm/hand system. Thus, at the end of Phase II, a simple, but capable and flexible telerobotic controller will be available on the marketplace for use with telerobots or automated robots (e.g. teach/learn) for several applications and several manipulator systems. A demonstration of the full OTCG is planned at AAMRL/WPAFB at the end of Phase II. ORBITEC intends to supply these systems to individual customers as well as robotic end-effector vendors.

As a result of the work done in the Phase I effort, the following recommendations are made:

1. The OTCG should be pursued for further development in a two-year, Phase II SBIR program.

2. The OTCG be analyzed, prototyped and tested as both a complimentary and a substitute device to other force feedback system approaches.

3. The Phase II program objectives should include: the development, assembly, testing, and demonstration of the OTCG-II unit that would be a precursor to a commercially available device.

4. This OTCG, designed in Phase I, should be developed such that the ORBITEC, WCSAR, and AAMRL laboratories can be used as testbeds.

The following suggestions are more detailed design issues which should be addressed in Phase II:

- Determination of the psychophysical midpoint of a human operating a vibro-tactile device.

- Conduct experiments which alter each of the following system parameters: displacement range, force, vibration magnitude and gain, pulsed frequency, stimulation area, stimulator location.

- Perform tasks which combine force, visual and vibro-tactile feedback.

- Provide stimulation at alternative sites.

- Vary temporal and spatial queues.

- Vary the amplitude, frequency, and contact force of the vibro-tactile elements.

- Configure a "real-world" experiment such as an undersea experiment in cooperation with NOSC.

- Build a joint with the sensor components integrated to verify the integrity of the joint design.

- Pursue the design of a bladder as the interface between the hand and the master controller.

- Investigate an automated calibration procedure for quickly obtaining the operator's finger link lengths.

- Build a passive compliant joint between the finger ring and the finger linkage.

The anticipated tasks of Phase II are as follows:

- Refine the Phase I design based on work completed between Phase I and Phase II (the State of Wisconsin will provide support for continuation of work between Phase I and Phase II

- Complete development of stimulation, sensor and position control system components

- Complete development of interface electronics hardware and software

- Develop testing protocol and test setup for both functional and human factors testing

- Test functional aspects of individual system components

- Integrate system components

- Perform productivity tests of the integrated system with human operator

- Modify the system components based on test results

- Demonstrate OTCG in WPAFB Laboratory.

After design and development of the prototype, functional tests provide proof that the individual components are performing as planned. If they are not, the problems must be debugged before integration and continuance of productivity tests. Some of the functionality tests will relate to performance with the human operator. Upon completion of the functionality testing, the components will be integrated and once again tested to make sure that each component functions properly within the integrated system. Only then will the system productivity test protocols be executed to determine the effectiveness of the system in an operational sense. Again modifications to the prototype may be instituted where needed. These iterative tasks will allow for

proper prototype development, testing and refinement such that the device may be used in demonstrations to potential customers in Phase III.

Several parallel developments may allow other testbed activities during or after the Phase II effort. The AAMRL lab may be used as a testbed to operate two telerobotic arms and hands. The Oak Ridge National Laboratory may be useful as a testbed for the Army Soldier--Robot applications. The NASA Flight Telerobotic Servicer system developments may be used to test the OTCG at the Goddard Space Flight Center. The NASA EVA Retriever may be a testbed for autonomous teach and learn systems. Other commercial robotics developers may wish to try the OTCG as a potential controller for their system.

ORBITEC's long-term goals are to commercialize technologies which emanate from our own research and development, from the Wisconsin Center for Space Automation and Robotics (WCSAR), and from other assets of the University of Wisconsin. The OTCG is an innovation to which ORBITEC is committing itself in governmental and commercial market places. This goal is supplemental to the overall goals of WCSAR which includes research in the development of component technologies. Thus, ORBITEC's objectives fill the gap between the pure research of technologies and the innovative implementation of those technologies into a usable and economic product.

4.0 POTENTIAL FOR PRACTICAL IMPLEMENTATION

4.1 Practical Applications

Automation and Robotics (A&R) technologies have been the focus of much research and development in recent years to increase operational productivity and capability in several areas. One sector of developments have focussed on "human-in-the-loop" control and operation of remote robotic "slaves". These "telerobotic" systems may be very useful in situations that present danger to humans or difficult access by humans (e.g. hazardous nuclear, chemical, and biological contaminated environments; space; deep sea; nuclear plants), and have complex non-repetitive operations that are difficult to automate. Several telerobots to date have followed anthropomorphic design to minimize the physical variances between the human operator and the telerobot slave. The OTCG has great potential for wide spread applications because of its projected low-cost, simplicity and ease of operation compared to other telerobotic control systems. The OTCG may also be used to augment the teleoperator performance in force reflective systems.

The primary application for OTCG technology is for assured ability to service, maintain and operate military aircraft in hazardous environments. Those environments may include the presence of toxic fuels, chemicals, biological agents and nuclear radiation. The environment may be too severe to consider the use of ground support personnel. These personnel could remain in a safe environment while controlling the telerobotic systems, provided those systems possess near-human equivalent capabilities. One of the keys to the success of this strategy is the development significantly improved robot dexterity and the ability to precisely control the dexterous robot remotely. The glove controller proposed is a solution to many of the insufficiencies currently experienced in teleoperated robotics.

Other direct military applications include servicing and/or operation of Air Force, Army, Navy, and Marine aircraft/ground vehicles and equipment, munitions handling, and some combat applications. It could also applied widely in the electrical power, subsea and nuclear industries. Remote servicing and repair of on-orbit satellites/platforms for the USAF, SDIO and/or NASA could be significantly enhanced.

In addition, there is enormous potential for commercial terrestrial applications. A smart autonomous robot with advanced vision and sensory feedback capabilities could perform an almost infinite number of production tasks. These tasks would include: transporting, sorting, machining, assembly, inspection, and testing. The ability to perform these tasks would be limited only by the intelligence of the robot and its cost effectiveness for a particular task.

4.2 Technical Feasibility

The objective of the Phase I effort was to advance and refine the concept/theory of the OTCG concept, as necessary, to develop the foundation of critical knowledge to support the proof of feasibility of the technology and the system operational capability. The feasibility and foundation for the development of the OTCG for telerobotic applications is the long-term objective of this effort. During the Phase I SBIR effort, various key master controller glove components were designed, built and tested by ORBITEC. Preliminary requirements and design for a prototype glove system were established. Proof of concept feasibility was accomplished through systematic testing of the key components and overall concept analysis and definition.

The key issues that we needed to resolve in Phase I that related to technical feasibility were:

(1) How to design a simple, cost-effective, and light-weight, and versatile position control system for the human operator?

(2) Can the size of vibratory stimulators be reduced such that they can be accommodated on the inside surface of a fitted glove?

(3) Is it feasible to drive piezoelectric stimulators with enough dynamic response to effectively stimulate the hand without extremely high voltages?

(4) Can a human operator interpret/correlate vibration levels to input signals generated by sensors that would be located on the dexterous manipulator?

(5) Does vibro-tactile stimulation overstimulate and saturate the operator's sensing ability over time?

(6) How does one mount piezoelectric stimulators to achieve the optimum response?

(7) Are there practical alternatives to piezoelectric devices that can be used in this application?

(8) Can a practical vibro-tactile based telerobotic control system be designed and integrated with the position control system?

The Phase I work completed that directly relates to the above issues are briefly discussed below:

(1) Demonstrated that a simple, cost-effective, and light-weight position control system for each finger of the human operator could be designed. ORBITEC, with State of Wisconsin

support, developed a new, very small, low power, position rotation sensor which allowed a very light-weight linkage exoskeleton to monitor unique finger positions. A prototype was developed for a four-degree-of-freedom finger attached at the palm.

(2) ORBITEC determined that the size of vibratory stimulators can be reduced such that they can be accommodated on the inside surface of the control glove. Two methods were identified: piezoelectric resonators and electromagnetic solenoids. The piezoelectric elements used in Phase I prototypes were 1.2 cm in diameter. The electromechanical solenoids are less than 1 cm in diameter and may be integrated into an array of stimulators that will fit on the fingertip.

(3) The piezoelectric resonators provided reasonable dynamic response with a +/- 15 volt sine wave input. The most significant amplitude vibration was found using a glove or semi-rigid mount. Some piezoelectric stimulators operated in actual operator testing for many hours with no signs of degradation.

(4) ORBITEC determined that normal human operators can perceive the vibro-tactile stimulation and interpret the input to at least four levels of resolution with only a few minutes of orientation.

(5) Overstimulation of the operators fingers occurred more often with electromechanical stimulators which displayed a more non-resonant and noisy output when input voltages were increased beyond 40% full scale input. Ample stimulation was received by the operators without fatigue, if the stimulator was not driven beyond the clean, resonant acoustic output range.

(6) Several mounting approaches were investigated for the piezoelectric stimulators to achieve the optimum response. Optimum output was achieved in the fitted glove finger, and the semirigid washer backing configurations.

(7) We determined that there is a practical alternatives to piezoelectric devices that can be used in this application. The electromechanical solenoids appear to have a better dynamic response in a smaller area such that an array of vibratory stimulators could be developed to fit on the surface area of the fingertip. However, this stimulator array will be somewhat thicker than a piezoelectric array.

(8) We developed a preliminary design for a practical vibro-tactile based telerobotic control system. The results of this Phase I effort provide insight to a point design of the OTCG, which will allow human telerobotic control of a wide variety

of robotic end-effectors with appropriate feedback mechanisms. This design also may be easily integrated with existing arm/wrist controllers. The Phase II controller system would be used to control one of several robotic hands available today.

The Phase I effort has developed an excellent foundation from which to build on to the technology for the proposed OTCG prototype construction and testing in Phase II and the planned production of the system in Phase III. The Phase I project: (1) provided important conceptual and preliminary design results; (2) developed key components that enable a practical OTCG device; (3) provided basic proof-of-principle testing that demonstrated technical feasibility; (4) improved the theory and engineering analysis models; (5) developed a preliminary set of system requirements; and (6) developed a preliminary overall system design concept for Phase II.

APPENDIX A

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APPENDIX B

HUMAN SOMATOSENSORY PERCEPTION

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APPENDIX B. HUMAN SOMATOSENSORY PERCEPTION

The purpose of this section is to provide a brief overview of concepts and mechanisms in somatosensory perception. A review of cutaneous sensory mechanisms is presented in Section B.1, while Section B.2 presents some of the relevant concepts in cutaneous sensation. A discussion of factors which influence cutaneous sensitivity (Section B.3) then precedes an overview of factors which influence tactile sensitivity and perception (Section B.4) which are relevant to the current application of tactile feedback.

B.1 Overview of Cutaneous Sensory Mechanisms

The skin contains three basic types of receptors which convey information about the environment to the central nervous system (CNS); mechanoreceptors, thermoreceptors, and nociceptors.

The mechanoreceptors are highly sensitive to skin indentation and pressure, as well as to movement of skin hair. Mechanoreceptors can be classified into rapidly adapting and slowly adapting types (Iggo, 1982). Rapidly adapting mechanoreceptors are responsive to movement and code the velocity of movement by changes in cell discharge frequency. These cells respond only during movement, not when the skin is static. These receptors are present in both the hairy and the smooth hairless skin of the hands and feet (glabrous skin). These receptors include Pacinian corpuscles, hair follicle afferent units, and Meissner's corpuscles. Pacinian corpuscles are most sensitive to high frequency mechanical vibrations (70-1000 Hz), but are insensitive to sustained deformation of the skin or to changes in skin temperature. Meissner's corpuscles are present only in the dermal papillae of glabrous skin and are sensitive to velocity. These receptors respond to skin movements in the frequency range from 10-200 Hz. Hair follicle afferent receptors respond to hair movement and signal the amplitude, rate, and direction of displacement (Dawson and Enoch, 1984).

Slowly adapting mechanoreceptors respond during skin displacement similarly to the rapidly adapting cells. However, these cells also respond when the skin is no longer moving during displacement, but is being maintained in its displaced condition. Unlike the rapidly adapting receptors, they provide information about long term changes in the skin. Two types of slowly adapting mechanoreceptors exist, Merkel cells (in the epidermis) and Ruffini endings (in the dermis). Merkel cells adapt more quickly and fire in an irregular pattern. Ruffini cells are excited by stretching of the skin and fire in a steady stream. Both types of receptors are somewhat sensitive to changes in skin temperature (Iggo, 1982).

Thermoreceptors fire at a steady rate while skin temperature is constant, but increase or decrease discharge rate with temperature changes (Dawson and Enoch, 1984). They are insensitive

to mechanical stimuli and to pain-producing chemicals. Cold receptors increase their firing rate when temperatures fall. Warm receptors increase their discharge rate when temperatures rise. Cold receptors are maximally sensitive to temperatures from 25-30°C, while warm receptors are maximally sensitive to the 40-42°C range.

Nociceptors are pain detectors and are sensitive to high intensity stimulation (Sinclair, 1981). Mechanical nociceptors respond to pin pricks, to squeezing, and to crushing of the skin. Thermal nociceptors respond to both high and low skin temperatures, as well as to severe mechanical stimuli. Figure B-1 illustrates the various receptors and the different tissue layers of the skin.

B.2 Concepts in Cutaneous Sensation

There are several spatial and temporal factors which are basic concepts in the psychophysiological literature on cutaneous stimulation and perception. A few of these concepts will be introduced and briefly defined, to aid in the following discussion of tactile sensitivity and factors which can influence it in humans.

Temporal Factors:

1. Temporal Summation: temporal summation occurs in the first few seconds of stimulation and consists of the additive buildup of sensation before adaptation occurs. This is also referred to as temporal integration and is a period of maximal stimulus effectiveness (Corso, 1967).

2. Adaptation: when a stimulus is presented at a constant intensity level, the skin's sensitivity to that stimulus changes (Berlund and Berglund, 1970). Generally, the response decreases. Adaptation is not modifiable by learning, as it is simply a progressive change in receptor response rate to the stimulus. Yet, adaptation is modifiable by temporal and intensity factors. The general progression is for sensitivity to decrease with increasede exposure to the stimulus, until a constant level of sensitivity is reached. However, the time required to reach this constant level will vary depending on the intensity of the stimulus. The greater the stimulus intensity, the longer adaptation will take. There is also a relationship between the size of the area stimulated and time to adaptation. For cutaneous pressure, adaptation time decreases as the area stimulated becomes larger. However, as the intensity of the cutaneous pressure increases, adaptation time also increases (Corso, 1967)(see Tables B-1 and B-2).

3 Sensitivity to post-adaptation stimulation: when weak vibratory stimuli are presented to the skin, adaptation causes a greater decrease in sensitivity for subsequent weak as

opposed to strong stimuli. The sensitivity to subsequent strong stimuli is diminished very little by a weak adapting stimulus (Marks, 1974).

4. Recovery: recovery is the post-stimulation period of time during which the former state of sensitivity is recovered (Corso, 1967). The duration of recovery time is dependent on the stimulus duration, intensity, and area. In general, the longer adaptation takes, the longer recovery will take. Table B-1 illustrates the relationship between adaptation time and recovery time for several different body locations.

5. Afterimages: when cutaneous pressure is applied and then released, its afterimage is positive or similar to the sensation produced by the original stimulation. Temperature afterimages are also positive.

Spatial Factors:

1. Spatial summation: as the number of stimulated receptors increases spatial summation occurs, this can cause the perceived magnitude of the vibration to increase. Summation will also occur as the areal size of vibrotactile stimulation is increased, although the degree of summation diminishes at higher vibration magnitudes (Marks, 1974).

2. Spatial inhibition: when two stimuli are presented simultaneously, the sensory effects of the target stimulus can be reduced by the second stimulus. The degree of inhibition depends largely on the strength (intensity) of both the target and the non-target stimuli.

3. Local surface variations in sensitivity: skin varies greatly in sensitivity over different bodily locations (Weinstein, 1968). This is most likely related to differences in receptor densities across the body. An area with few receptors will have poorer sensitivity to weak stimulation than an area with many receptors. However, increases in sensation with increases in stimulus intensity can occur rapidly. At higher stimulation levels, local differences in skin sensitivity are smaller than they are for lower stimulation levels. See Table B-3 for the absolute pressure thresholds for various locations on the body.

B.3 Factors Influencing Cutaneous Sensitivity

The sensitivity of the skin of the hand is affected by various non-nervous cutaneous components. During mechanical stimulation, there is a primary skin indentation occurring at the point of contact along with a much wider, but shallower, secondary depression around the primary indentation. Because of this, even

a very slender probe can stimulate a greater number of receptors than are present at the point of contact along. Sensitivity is also influenced by skin pliability, which in turn, is influenced by the number of sweat glands in the region and by skin temperature (Green, et.al., 1979). Thresholds and sensitivity of the hand have been characterized as follows. Greatest sensitivity to pressure is found in the distal half of the little finger, while the palm is the least sensitive. This follows the pattern of afferent unit density in the hand; the palm has the lowest density of units, while the distal half of the fourth finger has the greatest density (Lofvenberg and Johansson, 1984). Because the fingertips are densely innervated with Pacinian corpuscles, they are much more sensitive to higher than lower frequencies of vibratory stimuli, and are more sensitive to stimulation with smaller contactors. Therefore, the fingertips would be more appropriate targets for higher frequency tactile feedback than would the palm.

Detection thresholds of different cutaneous receptors for mechanical stimulation of varying frequencies are illustrated in Figure B-2. From this figure it is also possible to determine the type of sensory receptor sensitive to each frequency level. This information is useful for determining either (1) an appropriate stimulation frequency to deliver to a particular body location, or (2) for determining an appropriate location for stimulation of a given frequency level.

B.4 Factors Influencing Tactile Sensitivity and Perception

Stimulus thresholds vary at different sizes on the body. A stimulus threshold is the intensity level which a stimulus must reach in order to generate a response from a sensory receptor. In general, skin with a more finely meshed lattice of receptors has a lower threshold than skin with a more loosely meshed receptor network. Skin thickness also affects sensitivity, as it affects the rate at which stimulus energy is transmitted. Thresholds also vary according to the extent, intensity, duration and rate of application of the stimulus. For instance, a low energy stimulus which fails to excite receptors, may cause them to fire if applied for a longer time, if it is applied to a greater surface area, if its intensity is increased, or if its pulse rate is increased (for a vibratory stimulus). The interactions among these variables are important to consider in the design of a tactile feedback stimulus mechanism.

Skin temperature affects touch and vibration thresholds (Marks, 1974). Cooling the skin decreases its sensitivity to weak stimulation, and even the roughest surfaces will seem less rough than they do at warmer temperatures. Warmth generally facilitates sensation while cold inhibits it. However, extreme warming also inhibits sensation. Temperature can also have a variable effect, depending on the type of vibration receptors involved. There are

low frequency (less than 80 Hz) receptors and high frequency (sensitive to vibrations over 70-80 Hz) receptors. Temperature appears to influence only the vibrotactile thresholds of high frequency receptors; low frequency receptors show no such change in sensitivity. Thus, it is the sensitivity of the Pacinian corpuscles which are affected by changes in skin temperature. Greatest sensitivity of these receptors is reached at 36-37°C, but show decline at higher temperatures. Therefore, it is important to consider the probably temperature environment on the skin; since different temperature ranges influence which skin receptors are the most responsive, and therefore, what type (frequency) of stimulation would be most effective.

Skin temperature is one factor which can influence vasodilation and, in turn, influence the sensitivity of the Pacinian corpuscle system to vibratory stimuli. Another factor which is thought to influence vasodilation and, thus, sensitivity, is progesterone level, which varies during the menstrual cycle in women (Gescheider, et.al., 1984). These cyclic changes have been shown to influence vibrotactile sensitivity, as well as sensitivity to heat, cold, pain, and performance on tactile spatial acuity tasks (Gescheider and Joelson, 1983). The nature and extent of such cyclic changes would be important to describe for the current, and future, tactile feedback systems.

The threshold of a skin site can also be influenced by the presence and nature of previous stimulation to that site (Verillo and Gescheider, 1977). For example, if two sequential but subthreshold stimuli are presented very closely in time, a sensation may be perceived. For vibratory stimuli, the effects of prior stimulation on subsequent stimulation to an area depend mainly on the frequency of the two stimuli. Stimulation by a low frequency stimulus does not affect the threshold produced by a subsequent high frequency stimulus unless the intensity of the low frequency signal is substantially raised. In this case, the second sensation will appear stronger (temporal summation). One explanation for this phenomenon is that only the high frequency (Pacinian) system is capable of temporal summation, and that it is capable of this at both threshold and suprathreshold levels of stimulation; while the low frequency system contributes in determining the sensation of magnitude for suprathreshold stimuli. These factors would be important to consider in a tactile feedback system which is designed to be linearly responsive, since consecutive subthreshold stimuli might still produce a sensation.

Practice can modify pressure and two-point thresholds. Tom (1973) found that practice lowered the two-point threshold. Interestingly, this practice effect held for both homolateral practice and for contralateral practice for a given body area. Variations in attention can also cause fluctuations in the thresholds of an individual, as can time of day. Thresholds appear to be much higher in the morning than in the afternoon (Sinclair,

1981). This latter effect might influence the scheduling of work requiring tactile feedback. It might be best to standardize the system for a given time of day and then schedule work within a reasonable range of this time, when possible.

There are sex differences and laterality differences in thresholds (Weinstein, 1968). Females have been found to have lower pressure thresholds than men on 20 body sites, and also have been found to have more sensitive point localization and two-point discrimination. Laterality differences for pressure and two-point discrimination tests, tend to show superior sensitivity on the left side of the body (Porac and Coran, 1981). These differences, however, might be influenced by practice with a given system. Unlike the laterality effects displayed for pressure and for two-point discrimination tests, there appear to be no differences in the way the two hands perceive roughness. Subjects are as accurate and quick in judging roughness with the left hand as with the right hand.

Age also affects thresholds. With increasing age, there is a rise in the pressure thresholds of the fingers and a decrease in ability to detect vibration (Sinclair, 1981). This could influence the selection of type of stimulation for different user age groups.

Spatial factors are also important to sensitivity and thresholds. Stimulus localization is more acute than two-point discrimination by 10-30 times, depending on which area of the body is stimulated (Loomis, 1981). It is extremely good on the fingertips and lips, but poor on the thighs and back. Visual information can be important for tactile localization, as blindfolded subjects sometimes have problems determining which of their fingers have been touched. Errors of localization are relatively common on the index finger, are most frequent in the middle finger, but do not occur on the thumb. Naturally, a relatively sensitive area should be used for tactile feedback when good discrimination is required.

Accuracy and reliability on the two-point discrimination test depend on several state factors at the time of the test. Accuracy can vary with different skin temperatures, practice on the task and subject fatigue or distraction.

Localization of thermal stimuli is much poorer than for tactile stimuli. Localization of thermal stimuli improves when presented concurrently with stimuli that mechanically excite the skin. However, if the tactile signal is inconsistent with the thermal sensation, the location of the tactile stimulation can mask that of the thermal signal. Referral of a thermal sensation to a non-stimulated locus can also occur (Green, 1978). Therefore, for a tactile feedback system, tactile stimuli would appear to be more effective than would thermal stimuli.

Reaction time varies inversely with the intensity of the stimulus for touch, warmth, and cold. It appears that the intensity of the sensation felt, rather than the intensity of the stimulus itself, is the critical factor. In general, the minimum reaction time which can be obtained from the hand is .1-.2 sec. for touch and .5 sec. or more for pain, warmth and cold (Sinclair, 1981). This also supports the selection of a tactile stimulus for feedback, over temperature stimuli or intense mechanical stimuli.

There is a finite limit to the number of individual vibratory stimuli which can be detected when presented in sequential fashion. At least 2 to 40 ms. must elapse between successive stimuli if they are to be distinguished and numerosity determined. Ability to determine numerosity can be facilitated by increasing stimulus intensity or by delivering successive pulses to several, rather than a single, location. When presented in this manner, the spatial information enhances the numerosity task performance (Lechelt, 1974). This is important to consider if it is desired to code information via the rate of the stimulus pulse train.

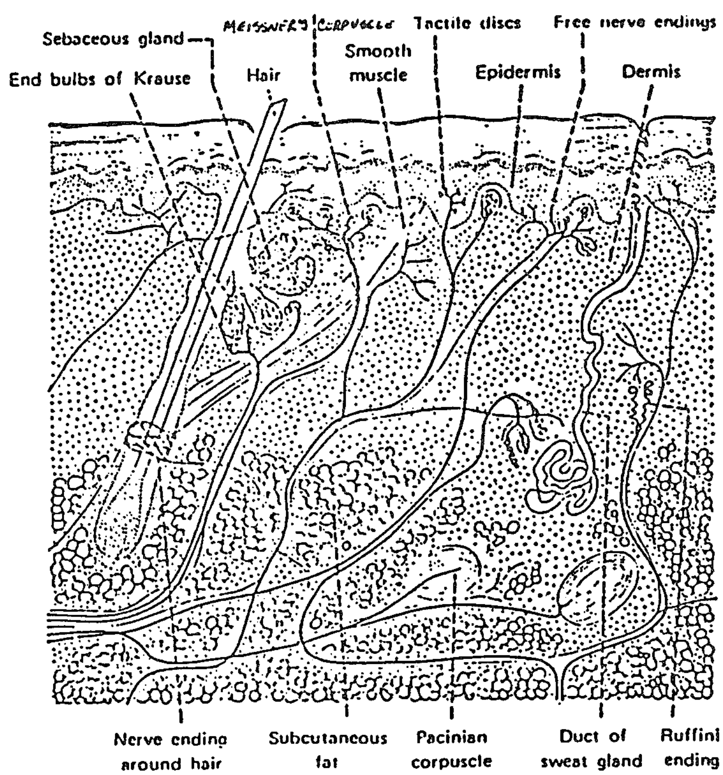
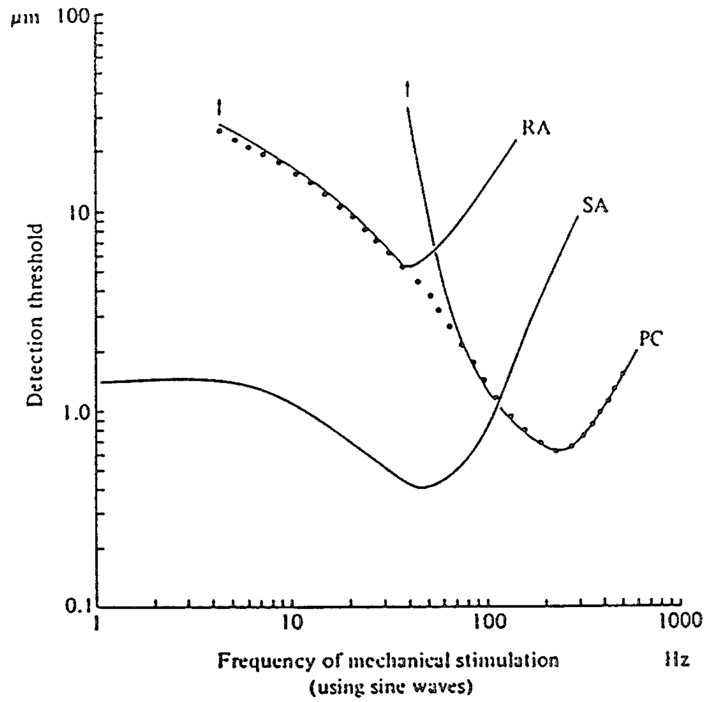


Figure B-1 Cross Sectional View of the Chief Layers of the Skin and Associated Nerve Endings



Detection thresholds (solid lines) for three kinds of cutaneous receptor (SA, slowly-adapting; RA, rapidly-adapting; PC, Pacinian corpuscles) at various frequencies of sinusoidal stimulation, and the detection thresholds (dots) for the sense of flutter (5–60 Hz) and of vibration (50–600 Hz) in human subjects. There is a close fit of the RA and flutter thresholds and of the PC and vibration thresholds.

Figure B - 2 Detection Thresholds for Three Types of Cutaneous Receptors

Part A: Adaptation				
		Bodily Location		
Stimulus (Mg)	Back of Hand	Forearm	Forehead	Cheek
50	2.4	2.3	5.1	5.7
100	3.8	3.3	6.2	6.4
500	6.0	4.9	10.0	11.6
1000	6.7	5.6	10.4	13.5
2000	9.5	7.8	16.0	19.4
Part B: Recovery				
		Bodily Location		
Stimulus (Mg)	Back of Hand	Forearm	Forehead	Cheek
50	4.3	3.4	5.3	3.9
100	5.8	4.0	7.0	5.5
500	6.7	6.2	10.2	8.0
1000	9.3	8.6	10.7	10.0
2000	11.8	9.3	13.3	11.9

Table B - 1 Adaptation and Recovery from Cutaneous Pressure

Stimulus Diameter (mm)	Region Stimulated	
	Forehead	Cheek
5	18.9	21.2
10	16.1	16.4
15	14.6	14.4
20	12.3	12.2
25	9.9	10.3

Table B - 2 Adaptation time from Cutaneous Pressures Over Different Areas

Bodily Region	Absolute Threshold (gm/sq mm)
Tip of the tongue	2
Tip of the finger	3
Back of the finger	5
Front of forearm	8
Back of hand	12
Calf of leg	16
Abdomen	26
Back of forearm	33
Loin	48
Thick parts of sole	250

Table B - 3 Absolute Pressure Thresholds of Various Regions of the Body

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